REGULATION OF THE GREAT LAKES

AND

EFFECT OF DIVERSIONS BY CHICAGO SANITARY DISTRICT

A REPORT BY

JOHN R. FREEMAN

CIVIL ENGINEER

1926

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(Revised June 16, 1915.)

REGULATION OF ELEVATION AND DISCHARGE OF THE GREAT LAKES

DESIGNS FOR GATES, SLUICES LOCKS, ETC. IN THE NIAGARA AND ST. CLAIR RIVERS

By

JOHN R. FREEMAN, Civil Engineer

DECEMBER 30, 1925

Revised to October 1, 1926

AKERMAN STANDARD PROVIDENCE

Providence, R. I., October 1, 1926.

To the President and Board of Trustees of
The Sanitary District of Chicago.

Gentlemen:

Since the discharge and dismemberment of the Engineering Board of Review as a whole, on March 28, 1925, I have taken the brief preliminary report prepared by me prior thereto and have expanded it greatly with the aid of my assistants. I am transmitting herewith the final results of my investigations.

In my research I have conferred with some of my former associates on the Engineering Board of Review, and with the engineers and experts of the U. S. Engineer Corps, the U. S. Weather Bureau, the U. S. Geological Survey, and others, both in the United States and Canada, asking for their constructive criticism. To those who have responded, I here give my grateful acknowledgment. However, I assume entire responsibility for this report, for the details of designs, inclusions, omissions, possible errors in data, and for stated conclusions, particularly with regard to the difficult and novel matters of earth-tilt and evaporation, and the changing fall from the surface of Lake Huron to the surface of Lake Erie.

I desire to record my appreciation of the assistance rendered me by Mr. Karl R. Kennison, consulting engineer, in computations on mass curves and the effects of regulation, and of the skill and diligence with which my assistant engineers, Mr. Alton C. Chick and Mr. John T. Doran have assisted in these studies.

I believe that the conclusions I have reached will stand the test of time and that this report can at least aid in crystallizing a practical line of progress in executing one of the greatest hydraulic projects ever before the world, the regulation of the Great Lakes.

Respectfully submitted,

John R. Freeman

Consulting Engineer.

BRIEF SUMMARY OF STUDIES AND FINDINGS

In brief, the main objects of the present study have been:

(1) To make sure of the truth regarding the extent to which the diversion of water through the Chicago Sanitary Canal has contributed to the recent lowering of the Great Lakes.

(2) To study in greater detail the best means by which this lowering caused by the Chicago diversion could be remedied.

(3) To give further study of the causes of the much greater lowering of all of the Great Lakes in recent years, amounting to three or four feet more than that caused by the Chicago Canal.

(4) To determine more completely the extent to which these greater changes in Lake Level could be controlled and remedied.

(5) To review with the greatest practicable completeness the various different causes which affect changes in lake levels, with a view to separately measuring their effects, and obtaining data for forecasting changes in elevations, or in discharge, so far as practicable.

(6) To further determine the range of elevation of each lake that would be most useful in an adjustment between the two conflicting purposes of:

> (a) Increasing the depth of water available for navigation.
>
> (b) Conserving the surplus water yield in years of large rainfall, by storing it for use in later years of small rainfall, so as to permit, at some future time, the largest practical development of water power along the St. Lawrence and Niagara Rivers.

(7) To develop designs for structures by means of which the levels of Lakes Erie, Michigan, and Huron could be quickly raised and subsequently controlled within the range of elevation found to present the most useful adjustment in meeting the two conflicting interests described in the preceding paragraph.

(8) To determine the extent to which both elevation and discharge of the lakes could be controlled by these structures within the limits of elevation of low water imposed by navigation and the limits to high water imposed by flowage damage, and under natural conditions of variation in rainfall, evaporation, lake discharge, ice obstruction, earth-tilt, winds, seiches, etc.

(9) To estimate the cost of these structures necessary for regulation of the levels and discharges of the several lakes.

(10) To study in detail many closely related subsidiary problems, as developed in course of the main lines of investigations described above, as for example:

(a) The preservation of Niagara Falls.

(b) Studies of the variation of rainfall from year to year.

(c) Studies of the amount of obstruction of outflow from the several lakes caused by ice-gorges.

(d) A determination of the amount and rate of evaporation from the surface of each Great Lake.

(e) The accuracy of the recorded measurements of lake elevations and discharges.

(f) The rate, and amount in recent years, of earth-tilt in the Great Lakes region.

(g) The effect of earth-tilt on future harbor depths and depths over the lock-sills at the Sault St. Marie.

CONCLUSIONS IN BRIEF

The more important conclusions and results of these supplementary studies may be anticipated, by stating here, briefly, that:

(1) Careful investigation shows that the total amount of lowering caused by the diversion of water through the Chicago Sanitary Canal, at any one of the Great Lakes: Huron, Michigan, Erie or Ontario, has been only about five inches. (See pages 214 to 219.)

(2) Meanwhile, the lowering in recent years due to natural causes such as changing climatic conditions, has amounted to about six times the amount of lowering caused by the diversion through the Chicago Sanitary Canal.

In other words, the recent changes in climatic conditions, chiefly in rainfall and evaporation, have caused the lakes to now stand between two and three feet lower than six or eight years ago.

(See pages 220 to 224.)

(3) The chief cause of the low lake levels now prevailing is found to have been a series of years of uncommonly small rainfall, and possibly more than ordinary evaporation.

From studying the ups and downs in the levels of all of the lakes found in the records of the past century, and particularly those found in the records of the past sixty-five years, it appears highly probable that we are now near to the lowest point in one of the great cycles of change which history shows have come on many previous occasions.

(See pages 39 to 44, and 220 to 221)

(4) There are records which show that on certain occasions about 100 years ago, several of the Great Lakes stood at about the same low levels as during the past year, and that in 1895, before the Chicago Canal was opened (or before the discharge of the Welland Canal was increased) they were also nearly as low as now.

Also in 1911 most of the lakes were at low levels.

(See pages 26 to 28.)

(5) There is every reason to expect from the behavior of lake levels during the past 65 or more years, in course of which they have presented cycles of years of low lake levels—from three to seven years in duration—followed by years of high lake levels, that soon the lakes will again begin to rise from natural causes, chief among which causes is a probable return of larger annual rainfall.

(6) Nevertheless, a careful review of the rainfall records at more than 50 stations in the Great Lakes region, some of which have been maintained continuously for more than 60 years, indicates that the average rainfall, in 5-year cycles, has been irregularly decreasing, at an average rate of 10% in 50 years. No good reason appears for thinking this will be permanent. (See pages 42 to 44.)

(7) Nothwithstanding the diversions by the Chicago Sanitary Canal and other canals were to continue at their present rate, all of the information available tends to prove that, in due course, the lake levels would all return to within about six inches of their former heights, except for the permanent lowering of any particular lake caused by earth-tilt, dredging and scour of its outlet channel, and the diminution of rainfall noted in the preceding paragraph.

(See page 223.)

(8) With the rate of draft at Chicago reduced to 4,167 cubic feet per second, the lowering of lake levels due to this diversion will be only about two and one-half inches below the height at which they would stand, were there no diversion whatever through the Chicago Sanitary Canal. (See page 218.)

(9) It is found practicable to raise and to control all of the Great Lakes at levels always at least two feet, or two and one-half feet, higher than the low levels repeatedly recorded in past years, by means of relatively simple and inexpensive structures at the outlets of the lakes, which structures could all be built within a period of five years and at costs that would be small in comparison with the direct gain in lessened cost of freight movement over the lakes.

(See pages 228 to 241, 273 to 285, and 314 to 338.)

(10) The estimated cost of the regulation works proposed in the Niagara River is about eight million dollars ($8,000,000.). The cost

of those proposed in the St. Clair River is about twenty-five million dollars ($25,000,000.).

Much apparently reliable evidence has been presented showing that the extra cost of freighting along the lakes due to the available depth being below normal, is about one-half million dollars per year per inch of deficiency, The figures presented by the Lake Carriers seem to prove that one foot loss or gain in depth of draft causes a loss or saving of six million dollars ($6,000,000) each year in cost of freighting. It is possible to gain two feet permanently by the works proposed, and gain three or four feet over the recent low levels.

(See pages 192 to 195.)

(11) No special studies or designs are presented in the present report for structures for controlling the level of Lake Superior or Lake Ontario, because Lake Superior is already fully provided with regulating gates, by which its outflow and its elevation can be controlled, and because at Lake Ontario, extended studies have been long in progress under an International Commission, for building regulation works located within the head of the St. Lawrence River, for the double purposes of development of water power, and the improvement of navigation. It is obvious that by means of such works the level of Lake Ontario could be controlled at any desired practicable elevation.

(See pages 247 to 251.)

(12) Alternative means are available for providing an increased depth for navigation:

- (a) By raising the lake levels to an elevation two or three feet higher than the low levels of past years.
- (b) By dredging shallow channels and harbors so as to permit the increase in depth of draft of the freight boats which ply these routes.
- (c) These two methods can be combined.

(See pages 228 to 231.)

(13) The designs for structures presented in this report have been worked out so as to permit the highest practicable range of operation in control of lake levels, because it was found that the added cost of building these structures so they could control up to the maximum height was an extremely small proportion of the entire cost of each structure, and that the saving by building to a less height would be unimportant. (See pages 230 and 231.)

(14) It is not proposed that within 10 years (and perhaps not within 25 years), that the lakes should be raised to the highest levels which these works will permit. The need for the last foot in the

highest possible levels will come only with a larger demand for development of water power on the Niagara and St. Lawrence Rivers, many years hence. (See pages 230 and 231.)

(15) In the meantime it is proposed only that the level shall not be permitted to fall below a certain pre-determined minimum, and that whenever a year of extra large rainfall occurs, the extra flowage of riparian lands shall be prevented by releasing the surplus through the new sluiceways, instead of holding this surplus in storage for use in later years of abnormally small rainfall.

(16) Prior to the time when utmost conservation of water yield is required for water power development on the St. Lawrence, it is expected that the narrow outlet gorges which now limit the rapidity of flood discharge from Lake Huron and Lake Erie will have been made wider and deeper for the aid of navigation by ships of deeper draft. This increase in possible rapidity of discharge of a great flood will permit safely holding the lakes at higher levels than before.

(See pages 293, 368 and 369.)

(17) The possibility of securing increased depth of navigation by means of dredging shallow channels and harbors has been recognized in these designs, and the decision as to the precise limit at which increasing the regulated height should stop, is left for future investigation, to be made at any convenient time within the next 10 years.

(See pages 231, 245 and 246.)

(18) These designs assume that, sooner or later, channels all of the way from Duluth and Port Arthur to the Atlantic ocean will be deepened, so as to permit of 25 feet depth of draft, possibly more, but in the meantime they are designed to most conveniently serve ships of the present maximum sizes found on the Great Lakes.

(See pages 181, 240.)

The largest ore-carrying ships on the Great Lakes are from 500 to 600 feet in length, and for the purpose of obtaining sufficient strength with this great length, are made of a depth such that they could just as well be loaded to from 21 feet to 24 feet depth of draft, or deeper than present channel depths permit. The designs presented in this report are adopted to serve for these greater depths and corresponding increase of cargo, which can be carried at small additional cost.

(See pages 190 and 191.)

(19) The possible diversion of a large quantity of water into the Great Lakes from streams now entering Hudson Bay, was brought to the attention of the Committee on Lake Levels, as a remedy for low lake levels, and as means of compensation for the diversion of water from the Lakes through the Chicago Sanitary Canal. This water, now flowing north, was to be turned south into the Great Lakes by

way of Lake Nipigon. It was suggested that a quantity of water equal to that now diverted at Chicago could be taken through a canal across the northern divide, from waters of the Albany and Ogoki Rivers, which now flow into Hudson Bay, and perform no useful service to mankind.

The Committee deemed that these possibilities, if as stated, were matters wholly within the discretion of the Canadian authorities, and that it was not within the proper limits of their investigations to make, or ask, for a reconnaissance supporting or disapproving this matter.

Such data as could be found in the maps of the region published by the Canadian Water Power and Reclamation Division, indicate that there is no reasonable probability that any diversion of this kind could be made large enough, or cheaply enough, to be of importance in the present problems. (See pages 14 to 16.)

(20) The problem of regulation of lake levels and discharges has greatly changed within the 13 years since regulation of Lake Erie was studied and reported upon by the International Waterways Commission, and has changed even more since the report of the U. S. Board of engineers on Deep Waterways, in 1900.

The wonderfully large and rapid development of hydro-electric power within the past 25 years and the possibilities of far larger water-power development within the next 25 years along the St. Lawrence and Niagara Rivers, open up new problems that had no part in the studies of engineers who made these earlier reports in 1900, 1910 and 1913. (See pages 250 to 262.)

(21) In these earlier studies, regulation of elevation of lake surface for the benefit of navigation, was the chief consideration.

In the new outlook, regulation of the rate of discharge of water from each lake, so as to produce the largest practicable uniform flow for water-power development along the Niagara and St. Lawrence Rivers, will in course of the next 25 years become a matter of equal importance. (See pages 250, 251.)

(22) The Warren Report (so-called) prepared under the supervision of the U. S. Army Engineers, published in 1921, has been found a most valuable treasury of data, and in many lines has been used as the starting point for several of the studies of the present report.

(See pages 252, 253.)

(23) The limits proposed in this report for high water and for low water on the Great Lakes, in brief, have been determined as follows:

It is assumed that the high water of 1838, which for many years past has been recorded in all of the U. S. Charts of the Great Lakes prepared for purposes of navigation, is at the maximum flowage height ever permissible, and should not be exceeded (except perhaps for a few minutes during a seiche or a great windstorm), under the greatest flood discharge into either lake from its drainage area, that might happen in the course of 100 years.

The Committee on Lake Levels made enquiry of the legal advisers of the Chicago Sanitary District about damages and authority for flowing to these former natural high lake levels, and were informed that so far as the fore-shore within the United States was concerned the U. S. Government possessed the rights of flowage.

(See pages 245 and 246.)

In order to provide a margin of safety for such great storms, or floods, or periods of excessive rainfall such as come once or twice in 100 years, the normal high water elevation adopted in these plans for lake regulation, is placed about one foot below this record high water of 1838. (See pages 230, 231, also 366 to 368.)

(24) A normal low water plane for each lake also is specified, this being placed about 2.5 feet higher than the recent low levels of Lakes Michigan and Huron, about 2 feet above that for Lake Erie, and about 1.5 feet above that for Superior. (Superior is at present held by means of the regulating gates at its outlet, at about a foot higher than the level at which it would stand were there no such artificial control.)

(See folding diagram following page 198.)

(25) The height of the proposed storage space between these planes of normal high water and normal low water, is 2.5 feet for Lakes Superior, Michigan, Huron and Ontario, and 1.5 feet for Lake Erie.

This space, 95,165 square miles in area and 2.4 feet average depth, between the planes of normal high water and normal low water, is proposed to be used for a storage reservoir for the regulation of the discharges of the Niagara and St. Lawrence River, so as to make these discharges more uniform and so as to increase their present extreme low water quantities by the release of water collected in years of more than ordinary rainfall, and held in this storage space until a period of small rainfall. (See pages 232 to 236.)

(26) The type of design adopted comprises a sort of dam made up of arched concrete sluiceways with clear openings each about 72 feet in width, closed wholly or partially by gates of structural steel plates and girders, hinged at the base, so they can lie flat on the bottom of the river when fully open, or can be raised by electrically-driven winches, through strong chains attached to their upper corners, to stand at any desired height. This type of drop-weir gate is believed

to present the greatest safety in permitting passages of ice or debris, freedom from obstruction by freezing, economy in cost, and facility of operation and beauty of appearance.

In the design for Niagara River, where no boats are to pass, a broad concrete highway bridge covers the concrete piers and sluiceways. In the St. Clair River, four locks, each as large or larger than those at Sault Ste. Marie, are incorporated, also an open slip or "fairway" through which boats can pass in a current of about 7.3 miles per hour (under extreme conditions), without lockage.

(See pages 270 to 284 and 314 to 339.)

(27) Much care has been taken in choosing the locations for these works so as to secure safety from causing ice-jams, and so that construction could be carried on without obstruction to commerce, and completed with all practicable dispatch.

(28) It is expected that the Niagara works would be built first, these being much the simpler and cheaper, and because of the importance of stopping the damage going on at Niagara Falls. Moreover, it is the regulation of Lake Erie that heretofore has received attention, and was recommended by the Board of Engineers on Rivers and Harbors in reviewing the Warren Report, but with works near the **head** of the Niagara River.

The location about 20 miles downstream, recommended in this report, also will require somewhat extensive changes at the entrance to the Erie Canal at Tonawanda, before gates are closed to their full height, and a dike and riverside boulevard are recommended as part of the project, but not included in the estimate of cost of $8,000,000.

(See pages 275, 276, 310 and 311.)

(29) By means of only the works in the Niagara River, after it is possible to operate them to their full height, a substantial improvement in depth for navigation in the Detroit and St. Clair River would be had, through the backing up of water from Lake Erie.

(30) No reason appears why the St. Clair works could not be carried on simultaneously and the entire project completed within three to five years, according to the energy expended.

The designs presented in the report are developed with such completeness that contracts on a unit-price basis could be let almost immediately after a few soundings and borings. (See page 330.)

(31) Immediately on completion of these works (or without waiting for entire completion of superstructure) the raising of lake level could be begun by partially closing the gates, in case nature has not by

that time remedied the present low levels through more copious rainfall.

(32) These designs for locks present many interesting features in the use of cylinder gates for filling and emptying, and particularly in the incorporation of the design of Dr. Krey and Professor de Thierry for introducing the lift-water at low velocity through a multitude of openings in the breast wall, instead of through channels in the side walls and floors.

The open Fairway, which is a sort of open venturi flume, for quick passage of boats without delays of lockage, also presents novel features of baffles on the floor, so disposed as to retard the current and at the same time cause a gentle spiral movement of the surface water up the sides and toward the middle, designed to fend off cakes of ice, or boats, from the side walls.

(See pages 316 to 320, and 330 to 332.)

(33) It is found that by use of the regulating works as proposed in the previous paragraph, and without any deepening of present channels or harbors by dredging, that the average depth available for navigation can be increased about two feet (much of the time, three feet) above the average depths prevailing during the navigation season in the years of smallest rainfall within the past 25 years, and that minimum levels for navigation can thus be made about two feet deeper (and the average depth made about three feet greater) than the average depth prior to the opening of the Chicago Sanitary Canal.

(See diagram, page 383.)

(34) Meanwhile, in addition to this gain in depth, the minimum daily discharge of the river at Niagara can be increased by 12½%, from 160,000 cu. ft. per sec. to 180,000 cu. ft. per sec., and a substantially uniform flow maintained at a rate of about 200,000 cu. ft. per sec. during the navigation season, or summer; and at about 180,000 cu. ft. per sec. during the winter, or non-navigation season.

(See pages 228, 229, 368 and 369.)

RAISING LEVELS VERSUS DREDGING CHANNELS

(35) As to the opposing methods of deepening existing channels by dredging versus increasing their present minimum depths by elevation of the water surface over their beds by means of regulation works, this report tries to make it clear, that there need be no haste in fixing the precise limit of the normal high water plane which each lake must not be allowed to exceed save in great emergencies. Successive increases can be tried out.

If it is found that the normal high water limit now proposed might cause excessive damage to structures on the fore-shore, or to land-drainage systems that may have been built in the cities around the Great Lakes during the recent years of low lake levels; then the same operating range of 2.5 feet (or 2.0 feet) between normal high water and normal low water planes (which it is necessary to provide for accommodating the varying rates of water yield in years respectively of large rainfall and of small rainfall, and for equalizing the rate of flow for power development and for scenic effect at Niagara) can be secured by a lowering of both the high and the low stages of operation, by means of deepening the shallow channels by dredging.

Obviously, if channels and harbors thus are deepened one foot, the regulated normal high water plane may be lowered one foot.

(See pages 245, 246.)

(36) Although the raising of the levels of all the lakes to above the proposed normal low-water plane should be accomplished at the earliest date practicable, the full measure of regulation **of discharge** will not be needed until many years hence, and until a large increase over the present development of water power has been made. For this reason the final decision about the respective elevations above sea level at which the normal high and normal low planes for regulation should be fixed, and the final adjustment of balance between costly dredging on one hand, and damage by flowage on the other, can be delayed perhaps for 20 years. (See pages 230 and 231.)

REGULATION WORKS VERSUS COMPENSATION WORKS

(37) In previous studies of works at the outlet of Lake Huron, and in studies for works at the outlet of Lake Erie proposed for counteracting the lowering caused by the Chicago diversion, the designs have been for **compensation works,** comprising a series of submerged weirs, which would restrict the channel of discharge, and thus raise the water upstream.

The present report strongly disapproves of these compensation obstructions and instead thereof urges **regulation works,** or control gates, by means of which the **discharge** can be regulated and the lake **elevation** put at any point desired.

The present report strongly recommends building works **now** which shall be so designed as to provide for **all future needs,** so far as these can now be foreseen, and proceeds to demonstrate that the cost of far-seeing improvement is not large, and involves no important first cost over temporizing.

It recommends that the regulating works be adapted for regulating to the greatest heights permissible, and meanwhile recognizes that, in future, dredging can be relied on to reduce the high water plane required for complete equalization of discharge for the utmost future development of hydro-electric power.

It is obvious, without argument, that regulation works can be made far more useful to both navigation and power than can compensation works. (See pages 175 to 179.)

(38) An extension of terminal harbor facilities, from Buffalo down the Niagara River about 20 miles, is provided for in the designs now presented, all to be of a depth sufficient for ocean ships, or others, of 25 feet depth of draft.

A vast water front open to shipping from lake or ocean can thus be provided for industrial development all along both shores of the upper Niagara River and upon the shores of Grand Island.

The harbor facilities at Buffalo are now greatly limited and restricted by scant space inside the breakwater.

(See pages 273 to 275.)

(39) By placing these Niagara regulation works about 20 miles downstream from the outlet of Lake Erie, a better opportunity is provided for quickly regulating the discharge for scenic effect over Niagara Falls, and for power development.

Also, an increased head having large future potential value is provided for the several water-power developments.

(See pages 271 to 273.)

(40) This location proposed for the Lake Erie regulation works also greatly facilitates the repair of the damaged crest of the Horse Shoe Fall at Niagara, and the prevention of its future self-destruction by errosion at the deep gap, which now is going on at a rate which ultimately would greatly impair its scenic grandeur.

By the arrangement of works now proposed and its design of gates, the channel above either the Canadian Fall, or the American Fall, can at short notice be unwatered for a few days, while repairs are being made at much smaller cost than would otherwise be possible.

(See pages 270 and 271.)

(41) It is proposed to combine with these regulation works a commodious arched concrete bridge across the Niagara River at a location about one mile upstream from the Falls, and to lay out all of these new structures with most careful regard to scenic effects.

(See page 270.)

(42) International control is recommended for all of the regulation works on all of the Great Lakes. Obviously, executive authority should be concentrated in a small committee, for promptness of action,

such that the water from Superior can in effect be made immediately available for meeting a deficiency in Lake Erie. Promptness in adjustment of regulation may be of great value in times of exceptional floods coming into only one of the lakes, and in general may be useful in adjusting and compensating for differences in rainfall in any one season, over the different drainage areas of the several lakes.

(See pages 21 and 182.)

(43) Collection of data regarding lake levels and discharge has been made from every available reliable source, and is presented in condensed form in this report. Particular attention has been given to presenting the yield of the Niagara River month by month for the past 65 years, in convenient form for reference in the future, because this forms the only safe foundation for estimates about regulating the discharge, for the benefit of both navigation and future power development.

(See pages 195 to 199, also tables, pages 364 to 365.)

(44) The accuracy and precision of gagings of discharge of the several lakes have been reviewed with much care. It is found that the gagings of discharge of Lake Erie through the Niagara River, made under the supervision of the U. S. Army Engineers by assistant engineers E. E. Haskell, F. C. Shenehon, and L. C. Sabin, are doubtless the most accurate and precise gagings of a great river, that have been made anywhere in the world.

The connecting up of these gagings of discharge to the hourly and monthly observations of lake levels recorded during the past 65 years also has been carefully reviewed. The one important source of error is found in the uncertainty of the retardation of flow caused at times by ice, particularly in the St. Clair River. This matter was relatively unimportant for the problems of improvement of navigation, but becomes of great importance in studying the regulation of discharge for power development.

These gagings of the Lake Erie water-yield, as a whole, together with the similar observations at the outlets of the other Great Lakes, furnish an admirably complete and satisfactory basis for estimating the performance of the proposed works in regulating both the elevation and the discharge. (See pages 195 to 197.)

(45) Moreover, these river discharge gagings, in connection with observations of lake level, provide a trustworthy basis for determining the precise amount by which the levels of each lake will be lowered by the diversion of any stated quantity of water, in cubic feet per second, through either the Chicago Sanitary Canal, the Welland Canal, or the Erie Canal, and also the Power Canals at Niagara.

(See pages 210 to 217.)

(46) The causes of recent changes and lowering in lake levels have been carefully studied. A description is presented of each of the eight causes which may operate to modify the surface elevation, and some of which may happen to cause a sudden lowering and loss of depth, dangerous to ships navigating the shallow places in channels and harbors.

Many examples are presented, of great changes caused in the course of a few hours by strong winds and by barometric waves. Records are given of wind storms which have caused the eastern end of Lake Erie to stand for a brief period (perhaps for an hour) about 12 feet higher than its western end. (See pages 199 to 208.)

Seiches, or sudden change of water level caused by barometric waves, are described, and a record is given of one extreme seiche nearly midway of Lake Huron in May 1925, in which for a brief period, the water rose and fell through a range of 9 feet in elevation. This may perhaps have been caused by the meeting of two opposing water-currents that had been set in motion by the passing of barometric waves. (See page 188.)

SOME REMARKABLE EFFECTS OF EVAPORATION

(47) Very curiously no direct measurements of evaporation from the surface of any one of the Great Lakes appears to have ever been made. We have scant means of knowing how much more it may be in one year than in another, but plainly this may be an important factor in lake levels.

The importance of considering evaporation becomes plain when one realizes that there are long periods in each year during which more water goes up into the air from the Great Lakes by evaporation than the amount which flows down the Niagara or St. Lawrence Rivers.

It is not impossible that the amount evaporated on one day may be from two to four times as great as upon another day in the same week, both days being without rain.

The great areas of water surface, in relation to the drainage areas, cause evaporation to be a factor of uncommonly large importance in the outflow from the lakes. Fortunately, however, climatic conditions, particularly the low water temperatures in the northern parts, tend to make this loss of water small.

The conditions which effect evaporation from the Great Lakes are very different from those which control evaporation from ordinary lakes and reservoirs. In winter the Great Lakes do not freeze over, therefore they present vast areas of water, which, although at about

32° F., is relatively much warmer than the surrounding air, and from which evaporation occurs at a much more rapid rate than from the surface of ice or snow.

On the other hand, in early summer the water in the Great Lakes, particularly in Superior, is uncommonly cold, and much of the time is colder than the surrounding air. This greatly retards evaporation. Also, evaporation is retarded by the dense fogs on the northern lakes.

The general result is that evaporation from Superior and northerly portions of Huron and Michigan probably is greatest in mid-winter, and smallest in early-summer; or quite the opposite from what commonly is found elsewhere. More observations are needed to establish the facts with a high degree of precision and certainty.

The total depth evaporated in the course of a year is probably about two feet on Superior and a little more than three feet on Erie. (See pages 80 and 81.)

(48) The importance of this evaporation factor upon the water yield of the Great Lakes is shown by the fact that Lake Superior shows a negative water yield in mid-winter, because the **evaporation from it then exceeds the total inflow** of the tributary streams plus the precipitation on the surface of the lake. (The observed outflow comes from drawing down the lake.)

Lake Erie, lying in a warmer climate and being much more shallow, shows a negative yield in the late-summer.

For several months in almost every year, Lake Erie discharges less water than is delivered into it from Lake Huron by the St. Clair River, because evaporation from its large area exceeds the inflow from all of its local tributaries. (See pages 48 to 54.)

(49) Ordinary methods of estimating evaporation, from temperature of air, etc., are found unreliable when applied to the broad surfaces, open winter areas, and extremely cold water over the deeper portions of the Great Lakes.

This evaporation from the Great Lakes, shown by the best data available, is so unusual and so important that its effect has been studied in great detail in this report. Two entirely independent estimates have been made of its amount; the first estimate has been made solely by hydrographic methods, by an analysis of comparisons of gagings of the inflow and outflow in and from each lake; the second estimate rests solely on meteorologic data and upon estimates of evaporation made from temperatures of dew-point, of air and water, and from the best available records of wind velocity.

These two very different methods of estimate each have been worked out in great detail, and the results are found to agree remarkably well in view of the uncertainties about discharge gagings in winter, the lack of certainty about water temperatures, and the irregular presence of vast fog banks over the lakes. More information is greatly needed about wind, fog, water temperatures, and ice-cover. (See pages 65 to 80 and 129 to 149.)

(50) These data, methods, and results of estimates on evaporation from the Great Lakes, although at variance with all observations found on evaporation from ordinary reservoirs, are presented with much fullness of detail in the hope that this presentation, showing what data we have, and what data we lack, may interest someone to make careful measurements of the actual depths evaporated during two or three complete years from at least Lakes Superior and Erie, the two extreme cases, where the present writer has been forced to deduce the probable evaporation month by month by indirect means.

EARTH-TILT

(51) This is found to be a matter of great importance in its relation to lake levels and the preservation of depths for navigation in the northern harbors of Lakes Superior and Huron, and over the lower sills of the locks at the Sault Ste. Marie. Its investigation has been strangely neglected.

Geologists and others who have studied the ancient beaches around the northern shores of the Great Lakes long have been agreed that uplift, amounting to several hundred feet near the Straits of Mackinac and around Georgian Bay, had occurred since glacial times, and several observers long ago had noted the different characteristics at the mouths of streams discharging into Superior from its northern and southerly sides at their entrance to the lake, the northern streams presenting a sharp declivity, while the mouths of the streams entering from the south were sluggish and deep. This plainly suggested a progressive earth-tilt upward at the north, and downward at the south.

(52) One of the greatest of American geologists, the late Dr. Grove Karl Gilbert, more than 30 years ago became convinced that a change of level, or earth-tilt, **was still taking place.** Without success, he urged the superintendents of the U. S. Coast and Geodetic Survey, and the Director of the U. S. Lake Survey, to carefully investigate this matter.

Subsequently, Gilbert undertook some limited but extremely careful investigations on his own account, (or rather for the U. S. Geological Survey) by comparing the records of gage heights at points far apart on the same lake, observed 20 years before, with recent observations, and found distinct evidence of a northward uplift at the rate of about 0.4 feet per 100 miles per century. The Lake Survey officials aided Gilbert in securing these gage records. (See pages 158 to 162.)

(53) Other geologists doubted Gilbert's conclusions. One particularly careful and competent student of the geology of this region published a report stating that probably no movement of this kind had taken place within the historic period. One of the most competent of the engineers connected with the Great Lakes investigations dismissed Gilbert's conclusions as resting on too slight a foundation, but the late Professor Hayford, at the time of his death, was conducting researches for a more precise measurement of water levels, with the intention of studying this matter.

(54) The present writer took up the subject anew, with the advantage of 30 years further accumulation of data, and soon found that Dr. Gilbert's conclusions appeared fully justified and remarkably accurate. The writer thereupon took up the matter with officers of the U. S. Coast Survey, of the U. S. Geological Survey, and of the Lake Survey. It was found that the subject had recently been studied anew and independently by one of the assistant engineers of the Detroit office of the U. S. Lake Survey, Mr. Sherman Moore, who had found some strange changes going on in the relation of readings on gages far a part that he had carefully set. His results with a widespread series of comparisons also agreed closely with those Dr. Gilbert had obtained 30 years before.

These several studies are presented at length in this report, and prove unmistakably the existence of a hinge line somewhere south of Chicago and Cleveland, inclined about 18½ degrees to the north of west, and a definite, nearly uniform, progressive uplift of the land to the north as far as the lakes extend, at rates which may vary at localities several hundred miles apart, but which in general is about half-a-foot, or more, per 100 miles per century.

(See pages 167 to 170.)

(55) By drawing through the outlet of each lake a line parallel to this hinge line, and by measuring the distance from this outlet-axis line to various important points around the lake harbors, it is found that the depth over the lower sills of the locks at Sault Ste. Marie, probably is decreasing from this cause alone, at the rate of about one foot per 100 years (perhaps more), and that depths in the harbors of Port Arthur and around Georgian Bay are similarly becoming less. This is a very important practical matter, requiring further investigation. (See pages 154 to 156.)

(56) Meanwhile the depths in the harbors at Chicago and Cleveland are increasing from this progressive earth-tilt, probably at the rate of more than a foot in 100 years.

The problems of land drainage around South Chicago, and the delivery of drainage and sewage into the lakes at various points thus promise to become increasingly difficult because of this earth-tilt.

(See pages 154 and 155.)

(57) Since probably this movement has been going on slowly for more than 200 centuries since the retreat of the great glacier, due most likely to isostatic readjustment, it is likely to continue for another thousand years, by which time the problem of keeping water, which now seeks the St. Lawrence, away from Chicago might become serious, were it not possible to dredge deeply the St. Clair and Detroit Rivers. Cutting a deep, broad channel in the head of the Niagara River, would still give relief to Lake Erie, and serious loss of water to the Niagara and St. Lawrence power need not be feared from the present rate of motion, even at that remote date. (See page 160.)

Earth-tilt explains to a large extent the remarkable change in fall from Lake Huron to Lake Erie, as measured by gages a long way from the outlet, which has puzzled observers and caused much argument during the past 25 years.

(See pages 154 to 156.)

(59) In all of these studies now reported on lake discharge, change in elevation, evaporation, earth-tilt, etc., etc., a strong effort has been made to get as close to the basic facts as is now practicable, and to obtain the data for each of these several problems of regulation, all with greatest practicable certainty and precision.

Mass curves, or summation hydrographs for the discharge of Lake Erie have been worked out carefully for testing the effects of regulation of discharge.

Care also has been taken to set forth plainly the method of approach to each problem and the line of argument followed in its solution, so that this shall be a convenient reference book for data to those who may desire to work out other solutions and test them by the records of what has happened under the most extreme conditions yet known of flood, drought, ice, errosion or earth-tilt.

(60) The present report has been written out at great length in presenting and discussing records and deductions from these records in order to comply with the opinion expressed unanimously by members of the Engineering Board of Review, that it was desirable at this time to bring together and publish for convenient reference, all available data which promised to be useful, either in the present discussion, or in future discussions of lake levels; or useful in future studies for the conservation of the flow into the Great Lakes in years of more than ordinary rainfall, by storage over the Great Lakes, for use in increasing water-power development in the succeeding years of smaller rainfall, which are sure to come.

(61) The matters of earth-tilt, and of evaporation from these lakes, have been written up at great length, for the double purpose of:

(1) Making conveniently available all of the data that the present writer could find and

(2) For stimulating further research into these very practical and important problems, which seem to have been sadly neglected.

(62) The cause of the observed decrease in fall (now amounting to nearly one foot) between Lake Huron and Lake Erie has been a matter much discussed at one time and another during the past thirty years, with the development of strong differences of opinion.

Some have claimed that the enlargement of the gap in the rim of the basin (at the outlet of Huron and along down the St. Clair River), by dredging under Government agencies, for increasing depths for navigation, followed by increased natural erosion by currents after an assumed protecting skin of gravel had been removed by this dredging was chiefly responsible for this lowering of Lakes Huron and Michigan to the extent of about one foot, and that inasmuch as this dredging had apparently lowered Lakes Huron and Michigan more than the diversion of water by the Chicago Canal, the Sanitary District should not be called on to meet the entire cost of a remedy.

Others equally familiar with all of the circumstances, particularly the engineers in charge of these river improvements, have been strongly of the opinion that these improvements of channels by dredging and otherwise had had only an insignificant part in causing the change; and that not more than 2 to 4 inches at most, out of the whole, had been thus caused.

The conclusion reached in this report is that the observed change has resulted chiefly from three or four causes:

(1) The effect of earth-tilt on the gages used for recording the levels of the two lakes, which, unfortunately, were a long distance from the outlet of Lake Huron.

(2) The effect of a diminishing quantity of water discharged.

(3) The result, direct and indirect, of deepening of channels for navigation.

(4) Perhaps there has been a very small additional deepening of the channels in clay and sand caused by the currents set in motion by the propellers of the larger boats.

In conclusion, the writer is led to believe that probably the deepening of channels for navigation by dredging etc., has caused from 2 to 3 inches of this loss, or about the same amount as would be caused by the diversion of 4,167 c.f.s. at Chicago.

(See pages 199 to 209, 220 to 223 and 523.)

(63) The possible effect in lowering the lakes by cutting off the great forests of pine, which formerly covered large areas in northern Michigan, Wisconsin and Minnesota, tributary to the Great Lakes, has been sought by careful analysis of the change in water-yield and water-loss from year to year, without finding any definite proof of such effect.

The total water-loss by evaporation and by transpiration from trees and other verdure has been found remarkably constant for the several 5-year periods from 1860 to 1924 inclusive. (See Appendix 4, page 524.)

All of which is respectfully submitted,

John R. Freeman

May 15, 1926.

CONCERNING THE ENGINEERING BOARD OF REVIEW AND ITS COMMITTEE ON LAKE LEVELS

Since this report is published apart from the parent volume it may be useful to begin by telling just why it is made and who made it.

This Engineering Board of Review comprised twenty-eight engineering specialists in the several fields of Municipal Water Supply, Water Filtration, Sewage Disposal, Transportation, River Improvement, Waterpower Development, Public Service, City Planning, and General Engineering Construction, each of whom had had experience with important problems in one or more of these special fields at various localities in the United States, and several of whom were already familiar with the outlines of the present situation around the Great Lakes.

It was called together in October 1924 by the Trustees of the Sanitary District of Chicago, with the advice and co-operation of the Engineering staff of the District, for the purpose of reviewing conditions existing in relation to the disposal of the city's sewage through the Sanitary Canal by the method of dilution with water abstracted from Lake Michigan; this lake water, carrying a relatively small proportion of sewage being discharged into the Illinois River and ultimately into the Mississippi.

The low levels of all of the Great Lakes in recent years, averaging about 3 ft. lower than six or eight years ago (and in Lakes Michigan and Huron 4 ft. lower than 38 years ago), have caused serious injury to navigation and widespread concern, and attention has been directed to the diversion of water by the sanitary canal at Chicago. Many persons have been led to believe that this diversion is the principal cause of these low elevations,—which is not the truth. It is a fact, easily proved, that by far the greater part of the lowering has been due to a series of years of low rainfall and large evaporation and that the Chicago diversion has caused only about five inches out of the 36 inches (or 48 inches) of total lowering.

This Engineering Board of Review was asked to examine critically and thoroughly into present conditions and to advise the Trustees upon the best remedial measures for sanitary conditions; also it was requested to thoroughly determine the facts relative to the controversy about lowering of the lakes caused by this diversion and its injury to navigation and to other commercial and public interests; and asked to state how injuries from the actual lowering caused by Chicago's diversion, could best be remedied.

Also the Board was requested to make a careful study of various designs heretofore proposed for the **restoration of former high lake levels,** to review all of the conditions under which regulating works must operate; and finally to **recommend whatever improvements would best serve all public interests; not only for Chicago, but for the whole Great Lakes Region, to view these problems as on a broad horizon and try to find the best course of systematic development for a long future.**

The Trustees of the District had long recognized that present conditions pertaining to sewage disposal and protection of the purity of Chicago's water supply were unsatisfactory from many points of view; that methods of sewage disposal which were the most efficient, and the best methods known to the state of the art, 25 years ago, had become outgrown; that Sanitary Science had been advancing rapidly meanwhile; and in brief that a great emergency now existed here which threatened both the public health and the city's commercial interests, about which the difficulties were not well understood by the Citizens of Chicago or by the general public throughout the Great Lakes Region, and along the Illinois River.

By request of the chairman of the Board of Trustees of the Sanitary district, this investigation by this Engineering Board of Review, as far as practicable, was made independent of the various studies by the engineering organization of the Sanitary District; which, however, assisted the Board of Review in many ways, particularly in collecting historical data.

In order to collect facts and study remedial works more efficiently and promptly, the members of the Board of Review divided into ten principal committees, according to the lines of their professional experience, and to each committee was assigned certain special features of the investigation.

The three chief lines of division between these 10 committees, were:

(1) The sanitary problems, with the recommendation of a definite program of improvements, including estimates of costs of carrying out the recommendations.

(2) The hydraulic problems of Lake Levels, of Reversal of flood flow of Chicago River, of Water Power, Etc.

(3) The water transportation problem, between the Great Lakes and the Mississippi River by way of the Chicago Canal and the Illinios River.

One of these ten committees was charged with a study of the effect of the diversion of water from the Great Lakes and with finding the means by which injuries to navigation and to water power could best be remedied. This Committee on Lake Levels was composed of

John R. Freeman	Mem. Am. Soc. C. E.	Providence, R. I. (Chairman)
C. E. Grunsky	"	San Francisco (Vice-Chairman)
Francis Lee Stuart	"	New York, N. Y.
Arthur E. Morgan	"	Yellow Springs, Ohio
Richard R. Lyman	"	Salt Lake City, Utah
J. F. Hasskarl	"	Philadelphia, Pa.
Robert E. Horton	"	Albany, N. Y.

Following the report of January 23, 1925, in the preparation of which all above named participated, the writer of the present report, because of many years of experience as consulting engineer upon important hydraulic problems along the Niagara and St. Lawrence Rivers, was asked to prepare detailed designs for the proposed regulation works in the Niagara and St. Clair Rivers, the general scope and outlines of which had previously been approved by the whole committee, and to present in an orderly way for future reference the data leading up to these designs, including estimates of cost. This has largely been done since the Board of Review as a whole disbanded, soon after its report of January 23, 1925.

THE BACKGROUND OF THE PRESENT REPORT

In order to give a background it is appropriate to begin with a brief statement about the cause for presenting a series of successive reports; the first prepared hurriedly, although carefully, with others following separately at intervals, instead of waiting and presenting all in one thick volume.

The chief reason for this course was that in November and December 1924 there was particularly urgent need of an early report upon the chief sanitary features connected with the disposal of the city's sewage and need for a widespread statement of the truth about the small proportion of the recent lake-lowering actually caused by the diversion of water from Lake Michigan through the Sanitary Canal.

An immediate reduction of the quantity of water for diluting the sewage, **to one-half the number of cubic feet per second that had been used for years,** was threatened; and there was particularly urgent need of an authoritative statement about the vital need of continuing the present rate of diversion of water from Lake Michigan into the Sanitary Canal for dilution of sewage **until works could be built** for purifying a large part of this sewage, and there was also immediate need for an outline of a program for sewage treatment, with an estimate of its cost.

Because of the urgency of presenting definite advice regarding the serious effects upon the public health of Chicago which it was feared would follow a proposed restriction of the diversion to half its present quantity, or from nearly 10,000 cubic feet per second down to 4167 c.f.s. with the effect, in time of heavy rainfalls, of **throwing the city's sewage back into Lake Michigan,** which is the city's only possible source of water supply; and because of a request from the Trustees of the Sanitary District for prompt advice upon a program for improvements for better meeting present and future conditions of sewage disposal, by methods other than dilution, the Board of Review sought to first work out the data and conclusions on broad lines, so as to present its chief recommendations regarding sanitary matters to the Trustees at the earliest possible date, and planned to later work out various matters with much greater detail, and to collect engineering data for future plans.

On December 15, 1924, after its members had separately been working with great diligence upon their several problems for nearly two months, the whole Board of Review re-assembled in Chicago, and after another week of conference and discussion made a unanimous report to the Trustees of the Sanitary District of its principal recommendations on December 20th, without then taking time to systematically arrange the data or write out in detail the reasons on which these recommendations were based.

The members of the Board then again separated to individually make studies more in detail of the problems assigned to its several committees, and sub-committees, and re-assembled in New York City on January 14th, for a week of further conference and discussion.

In the meantime, however, the Federal Government had issued a restraining order against the diversion of more than 4167. cubic feet per second from Lake Michigan into the Sanitary Canal after a specific date, which, being only about half the diversion and dilution of recent years, presented to the citizens of Chicago a most serious situation and called for prompt presentation of a report which should make plain to citizens other than engineers, in fewest words possible, the technical bases for the recommendations made by the Engineering Board of Review in its report of December 20.

On January 23, 1925, the Engineering Board of Review presented a unanimous report on the technical bases of its conclusions which had been reported previously, on December 22, 1924; dealing briefly with all branches of the problems that had been submitted to it.

It was at that time (Jan. 23, 1925) deemed important that the report of each important committee be condensed into so few pages that all of these reports could be assembled within no more than 100 pages, for widespread circulation, for the information of the general public upon the main facts and reasons for its recommendations made on December 22, 1924. This severe condensation gave so few pages to the work of each committee that much material of great importance to the permanent record had to be left out.

It was recognized by all who had taken part in these investigations that this series of reports made by the Engineering Board of Review in January 1925 would not be the last on these several topics; that **ten**

or twenty years would be required to carry out the recommendations they had already made; that in the natural order of things there would be new developments as the city grows, and that later studies would be called for from time to time, for which the data and reasons that had led to the present recommendations would be useful. Therefore, it was decided that the strictly technical data of interest chiefly to the engineers, rather than to the non-technical general public, which had been collected, should be classified, amplified, and put into definite form for future investigators, published, and **so broadly distributed that it could not be forgotten or lost.**

As explaining the broad scope and the detail given to these studies at the request of the Trustees of the Chicago Sanitary District, and their desire that the committee go to the bottom of each important question, it may be remembered:

(1) So much mis-information had been broadcast attributing most of the recent lowering of Lake Levels to the taking away of water by the Chicago Sanitary Canal, whereas, in truth, **only about one-sixth part of this lowering had been caused by this diversion,** they desired the truth about the several causes of lowering, investigated and set forth in unmistakable terms.

(2) That certain engineers of highest standing had concluded after investigation, that fully as much lowering of Lakes Michigan and Huron had been caused by dredging for the improvement of Navigation, and subsequent scour, in the St. Clair and Detroit Rivers, as by the Chicago diversion, and **if so, Chicago should not be charged with all of the damage and cost of remedy.**

(3) That some years ago the Chicago Sanitary District had offered a large sum of money, to be expended upon works in the outlet of Lake Huron, and possibly also at outlets of Lakes Erie and Ontario, for the purpose of compensating for and raising the levels of these lakes to an amount equal to the lowering caused by its diversion **without at that time having any very definite information as to what type of structures would best serve this and other useful purposes, or their cost.**

(4) That the future prosperity of Chicago is deeply concerned in having any projects for improving navigation throughout the whole Great Lakes region **carried forward in the most efficient far-seeing and thorough manner.**

RELATION OF THIS TO OTHER REPORTS OF THE ENGINEERING BOARD OF REVIEW

The present report relates only to the elevations and discharges of the Great Lakes, and to designs of structures by which their regulation at higher levels and to more uniform discharge can be accomplished.

It is supplementary to the reports of the Engineering Board of Review of the Sanitary District of Chicago on the Lake Lowering Controversy and a Program of Remedial Measures, published January 23, 1925 and to its earlier report of December 20, 1924. It is presented in fulfilment of the statement upon pages 86 and 109 of the report of January 23, that definite plans were being prepared for visualizing and furnishing a basis for estimating costs of works at one of the possible locations on the St. Clair River, which would later be presented in appendices.

Many of the conclusions of this present report were foreshadowed in the preliminary report of "Recommendations, Findings, and Conclusions" published on December 20, 1924; and the conditions, which the works described in the present report are designed to meet, are described with some detail in the report already referred to, published by the Board of Review on January 23, 1925.

Also the Board, as advised by the Trustees, deemed it best that certain of the sub-committees proceed to elaborate their data and designs in still greater detail, into a permanent record, such that all of the facts and the lines of reasoning on which their conclusions were based might be available promptly and economically to other experts in the many and various additional investigations that are sure to follow before these great questions are settled, and in years to come. This is the reason for the fullness of data and detail to be given in the series of appendices published separately from the early reports.

PRELIMINARY VIEW BY COMMITTEE ON LAKE LEVELS

The members of this committee inspected conditions in Chicago and along the Sanitary Canal and down the Illinois River. They then visited the Sault Ste. Marie, crossed the Straits of Mackinac, inspected conditions at the outlets of Lake Huron, Lake Erie, and Lake Ontario, and at various points along the St. Clair, Detroit, Niagara, and St. Lawrence Rivers down as far as the Lachine Rapids and Montreal. Also they inspected all of the important electrical power developments on both sides of the Niagara and St. Lawrence Rivers, and the sites of prospective power developments.

Its members studied with particular care the so-called "Warren Report", made in response to Resolution No. 8 of the 65th Congress, published in 1921 by The Government Printing Office, on the "Diversion of Water from the Great Lakes and Niagara River;" comprising a Report of the Board of Engineers for Rivers and Harbors dated August 24, 1920; and a report by Col. J. G. Warren, Corps of Engineers, U. S. Army, dated August 30, 1919, with extensive appendices by W. S. Richmond, U. S. Assistant Engineer.

This volume ("The Warren Report") presents a vast amount of historical and statistical data relative to the navigable channels of the Great Lakes Region. It includes results of special investigations on the various diversions for navigation, for sanitary purposes and for power, and their effects in lowering the lakes; and includes a particularly valuable and interesting study by Lieut. Albert B. Jones, Corps of Engineers, on the Preservation of the Scenic Beauty of Niagara Falls. As was said by the present Chief of U. S. Army Engineers, "This report is the only comprehensive and thorough investigation of all these subjects ever made and possesses great value not only from the technical, but also from the very full historical presentation of the matters with which it deals."

Also the members of this committee reviewed the many volumes of records of testimony of various experts called in litigation over the Chicago Diversion, presented in the Transcript of Record before the Supreme Court of the United States, October term, 1923. Its members studied files of newspaper reports of public meetings held to consider the causes and remedies for low lake levels, and invited the presentation of individual views from representatives of the navigation interests and water power interests. Its members individually reviewed a large number of reports of the U. S. Chief of Engineers, and of the U. S. Great Lakes Survey, also many reports of various Boards and Committees, and conferred with individuals familiar with conditions along the Great Lakes and the Niagara and St. Lawrence Rivers.

It appointed a sub-committee to collect adverse opinions on the diversion and lake-lowering controversy.

The committee met repeatedly for conference, and divided its several problems among sub-committees of its members, and sought in every practical way to become fully informed.

The outlines of the designs published in this present report were submitted to the members of the Committee on Lake Levels and to nearly all other members of the Engineering Board of Review, in a preliminary form at its final meeting in New York, and certain of the results of the hydraulic computations concerning the effect of regulation in increasing the depths available for navigation and in increasing the flow available for water power development, were published in the report of January 23, 1925.

Blue prints and photostat copies of many of the principal drawings and tables, as developed, have been submitted from time to time to engineers of the American and Canadian Power companies at Niagara, to the U. S. Chief of Engineers and to the Army Engineers in charge of the Lake Survey office, and to others with a request for constructive criticism and suggestions.

The degree of detail with which data, designs and reasons are now presented, with no claim that these are not subject to improvement, comes from an earnest purpose to bring the important facts about Lake levels and their control, into the fullest publicity, so that with a long view to the future:

(1) The best way may be found toward securing the greatest practicable benefits to the people of the United States and Canada.

(2) A definite policy regarding all of these improvements may be established forthwith by friendly conference between the two countries.

(3) Work may be promptly begun, and so carried forward toward the needs of a half century hence, that nothing once well done will have to be undone, or left to impair the full measure of benefits.

It is recognized that there are two fundamentally different methods of treatment possible for securing the objectives of

(1) Increasing depths for navigation.

(2) Preserving an amount of rise and fall in the levels of all of the lakes which will permit improving the regularity of flow, and increasing the discharge in seasons, or years, of small rainfall, by conserving and storing for a time, the surplus water yield from years of more than ordinary rainfall.

The first method, which certainly is the quickest, and probably is the most efficient and economical, is by raising the general levels and holding them up much of the time to the recent levels of years of large rainfall, and later on, possibly a foot higher than this, when demand for waterpower has grown.

The second method is by a general deepening of all important channels and harbors, by dredging, so that the lakes may in general be prevented from rising higher than in very recent years of large rainfall, while still gaining increased depth for navigation, and an extreme rise and fall for purposes of storage and release, and regulation of discharge, substantially the same as by the first method; but all within a zone of heights at perhaps 2 feet less elevation above sea level than in the first method; thereby avoiding trouble to sewer outfalls that may have been built too low, and avoiding interference with structures which have been built upon the fore-shore, in times of long-continued low water; and at the same time facilitating land drainage.

The structures, designs for which are now presented, are adapted to perform successfully under either method. They are designed tall, to accommodate the first method, but can be regulated to work in harmony with the second method.

Whatever method is followed, provision must be made for a rise and fall of lake surfaces of about 1.0 foot between January, July and December of each year, and for an additional rise and fall of about 2 feet to provide for receiving the surplus water yield in years of large rainfall.

Regulation to a more uniform height than with ups and downs of one foot between summer and winter is a physical impossibility.

And beyond this range there must be a margin of safety for such great floods as come about once in a half-century.

POSSIBLE DIVERSIONS INTO THE GREAT LAKES FROM CANADIAN DRAINAGE AREA NORTH OF LAKE SUPERIOR

Soon after these studies began it was urged upon the attention of members of this committee, by men apparently well informed, that there are Canadian streams now flowing northward into Hudson Bay and James Bay and now serving no particular service to mankind, which could be diverted into Lake Superior and thus add to the quantity of water available for power, while restoring lake levels and replacing wholly, or in large part, the quantity of water diverted by Chicago.

It was stated that certain of these north-flowing rivers traverse a relatively unsettled and inhospitable region, giving but a minimum of industrial opportunity. It was stated that these rivers drain a great table land along the divide, which has a unique and elementary drainage, not deeply cut, containing a surprising number of lakes which drain both ways, and that the major rapids occur on the borders of the table land, with large drainage areas at substantially the same elevation which might be united; that the Ottawa River has its source in a portion of this region, draining it to the south, but that north from Lake Superior and Lake Huron there seem to be large areas, the drainage of which now flows north, that could be given southward drainage into rivers tributary to the Great Lakes, which now receive only a small share, and that this could be accomplished by means of relatively low and inexpensive dams. It was stated that power interests on the Nipigon River, already are planning to divert some of this water southward, and that surveys in detail probably would show several important opportunities for such diversions.*

The fall from Lake Nipigon to Lake Superior is 255 feet. The present ordinary low flow is reported to be 5,800 c.f.s.; and the present development, one of about 50,000 horsepower capacity.

It was suggested that a money contribution from Chicago toward the cost of replacing, by this means, the water which it had diverted, might help various Canadian and American interests.

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*An outline plan has since been proposed by a Canadian, Mr. C. Lorne Campbell, for dams across the Albany River and its tributary, the Ogoki River, by which he believes a vast lake could be formed within the watershed, A. B. C. D. (see map, page 15), that could be drained into Lake Nipigon by a canal and add a larger flow than that diverted at Chicago and into the Welland Canal; with possibilities of vast additional power developments in Canada on the Nipigon River, and great opportunities for wood pulp and paper manufacture. The pamphlet, published in October, 1925, by W. J. Laut, of Toronto, setting forth these prospects, presents no engineering data of surveys, levels, water measurements, or cost estimates, on which to base its claims, **which in the absence of definite data, appear very extravagant to the present writer.**

The Committee deemed it unwise to, itself, go into these possibilities, although plainly it is desirable to have all such opportunities investigated.

Probably sooner or later the Canadian Government will make a full survey; but obviously, not even a field reconnaissance was within the proper activities of this committee.

The following map, which was prepared for another purpose, outlines the situation and shows that the Canadian Water Power and Reclamation Service has already been studying this region.

So far as can be judged from this map, the drainage area, the practicable area of the new lake, and the yield, each would be smaller than that of Lake Nipigon.

The new northern line of the Canadian National Railways traverses the midst of this territory, and one of the largest wood pulp and paper mills in America, the Abitibi, has recently been built on one of these north-flowing rivers; while on another has been built the Metagami Sulphite Pulp Mill, also one of the largest of its kind.

Since there may be other opportunities for industrial development on north-flowing rivers, the Canadians naturally would be slow to make southward diversions into the Great Lakes drainage, pending future development of the country; except where helpful to power development on south-flowing rivers like the Nipigon.

Whatever water can thus be diverted into the Great Lakes will not in any way conflict with the designs now presented, but would add to their benefits.

Note.—Long after the above was written and in type, an interesting account of this proposition, was presented in Engineering News-Record of March 4, 1926, pages 358-360 entitled "Analysis of Plan to form a Sixth Great Lake in Canada."

This states that since the pamphlet above referred to, descriptive of the Campbell plan, "has been given wide circulation and is made the basis of 'boiler plate' stories fed to syndicated papers, engineers should know what there is in it."

This analysis in the News finds:

Lake Nipigon is at elevation 852 ft. above sea or 250 ft. higher than Lake Superior.

The crest of the divide between Nipigon and Ogoki River is at something over 1,100 ft. or about 250 ft. higher than Lake Nipigon.

So far as maps show, the lowest gap is at Summit Lake although exploration might show something lower.

The estimated discharge of the Ogoki River at Army Falls, where the drop is 25 ft., from 6,000 sq. miles is estimated roughly at a mean of 6,000 c.f.s. and a minimum of 3,200 c.f.s.

The Albany River, at Lake Atikokiwam estimated at elev. 1,160 ft., has about 6,000 sq. miles of drainage and a mean run-off of about 6,000 c.f.s.

The flooded area probably could not exceed 6,000 sq. miles.

The probable cost of diverting 12,000 c.f.s. probably would be about $155,000,000.

Obviously, at any such enormous cost, a project like this is impracticable and it remains for the proponents to prove that it could be done for less, by accurate surveys levels and estimates.

CANADIAN STREAM FLOW GAGINGS

It is of interest to note the relatively small total depth of run-off, in inches on drainage area, for the climatic year ending September 30, 1922, shown by the small figures on the map on the previous page, at the several gaging stations in the vicinity of Lake Nipigon and the proposed new lake, in comparison with those further to the southeast.

The excellent general concurrence of the results of gagings from adjacent drainage areas also is of interest as tending to give confidence in the general accuracy of measurement.

THE PRESENT PROBLEM

This report deals principally with controlling the mean elevation of the water surface in each of the Great Lakes, as in a storage reservoir, by the closing and opening of gates and sluiceways to be constructed upon the Niagara and St. Clair Rivers, which are the outlets of Lakes Erie and Huron, for regulating their discharge. There are four distinct but inter-related problems pertaining respectively to:—

(1) Securing greater elevation and depth for navigation, and

(2) Obtaining a larger minimum discharge for hydro-electric power.

(3) Preserving Niagara Falls from self-injury, and adding to their scenic grandeur and beauty by taking water from the deep gap at the apex of the Horse Shoe Fall and spreading it over the denuded ends of both the American and the Canadian Falls.

(4) Restoring the Great Lakes to higher levels at the earliest practicable date, instead of waiting an uncertain length of time for the recurrence of years of large rainfall or small evaporation.

Already there are gates at the outlet of Lake Superior, and independently of this investigation, gates have been proposed below the outlet of Lake Ontario, in connection with other works on the St. Lawrence, now under active study by an international committee, for the double purpose of development of power and for opening channels for navigation 25 or 30 ft. deep, between the Great Lakes and the Atlantic Ocean.

The study now to be reported demonstrates that regulating gates and sluiceways upon the outlets of each of the Great Lakes are practicable and can be built at a cost that is small in proportion to their benefits and earnings for commerce and industry, and that the works proposed can accomplish the several purposes:

(1) Of quickly and permanently raising the level of the lake and river surfaces for increasing the depth of navigation channels.

(2) Of conserving and storing the surplus yield in years of abundant rainfall, and in the following years of smaller rainfall releasing more or less of this stored water for increased development of water power and for increasing the depths at low stages for navigation in the St. Lawrence River below Montreal.

(3) Of forthwith holding back a considerable part of the natural discharge during the season of no navigation, and of holding

back more or less of the Niagara discharge for the six hours after 11 p. m. **until the present lowering** of about 3 or 4 feet, which was caused chiefly by climatic conditions, **has been remedied.**

The problems of regulation, within the 15 years since the report of the International Waterways Commission on the Regulation of Lake Erie, and within the 25 years since the report of the Board of Engineers on Deep Waterways, have come to have far greater practical importance than they had at the time of these previous investigations; for several reasons, among which are:

(1) The marvellous increase and the growing demands for hydroelectric power.

(2) The greater and increasing demands of commerce.

(3) The more rapid self-destruction of the grand spectacle of Niagara Falls by erosion in the deep notch.

(4) In course of nature, since the investigations of 1896–9 there have occurred two cycles of years of smaller natural water-yield than those on which these earlier investigators had to base their estimates.

Some writers in the past, dismayed at the complexity of the problem of regulating the discharge and elevation of the Great Lakes so as to provide against trouble in their complicated reactions upon one another under varying conditions of rainfall upon the several drainage areas, which they had not opportunity to work out fully, have feared it was impossible to regulate the lakes better than nature is already doing; but almost any engineer skilled in such matters who will seriously study the records of the past sixty-five years and patiently go through the long series of computations showing the effect of operating these works as now proposed, will be convinced of the safety and feasibility of greatly improving present conditions at relatively small cost.

REGULATING THE ELEVATION

Control of elevation of the Great Lakes has been considered heretofore in only a limited way, chiefly in relation to the needs of navigation. In Lake Superior, the regulation works recently built in the form of Stoney gates, apparently were designed to give partial and not maximum benefits. In Lakes Michigan and Huron, the problem heretofore has been that of compensating works, or submerged weirs, sufficient to offset the effect of the Chicago diversion. The study on "Regulation of Lake Erie," reported by the International Waterways Commission in 1910 was limited in scope. There has, heretofore, been no comprehensive study of budget and expenditure of the waters of all the Great Lakes for maximum public benefit, except that by Mr. Francis C. Shenehon, described in the latter part of this report on Regulation of Niagara and St. Lawrence Rivers, 1919, pages 35-41 and 65-71.

The object of the present study is to raise quickly the level of each of the Great Lakes and to ever afterward hold each lake continuously at the highest practicable level consistent with riparian rights and the greatest beneficial use to the people of Canada and the United States for betterment of navigation conditions and promotion of maximum economy of water power development.

This study has continually in view, the probable demands of the distant future, and providing for ultimately getting the utmost value out of the resources that Nature presents.

HIGH AND LOW LIMITS

For the future maximum, the high water of 1838 is taken as standard. Almost from time immemorial this elevation has been printed on all of the charts for each lake issued by the United States Government, as indicative of what probably has happened in the past and what may happen again.

It has been stated by counsel learned in the law that whoever in time of low lake levels has built structures that might be injured by a return to this high water level of 1838 has done so at his own risk. Nevertheless, a margin of safety has been provided that will be encroached upon only for a month or two, once in many years, which margin amounts to nearly one foot between this "High-water of 1838" and the proposed normal high water.

(Obviously these limits for normal high and normal low water could be both moved down one foot or two feet, if ship-channels are correspondingly deepened, and lake outlets for Huron and Erie enlarged.)

For the future minimum, or normal low water, elevations have been adopted as shown on the diagram of lake heights which follows page 198. In general, this normal low water is two feet higher than the heights that have recently prevailed.

Various factors which control the range in elevation are discussed more fully on pages which follow, particularly on page 230.

Obviously, the height at which the water level may be held in each lake may be as great as the structures along the shores of the lake, its harbors, and its connecting rivers, will permit; but in working up to the highest possible limit, care must be taken both in design and operation of structures, lest if held at the highest possible limit, the lake rise too high after such an extraordinary series of large rainfalls as occur only once or twice in a century.

This margin of safety can be provided

(1) In part by excess capacity of sluiceways,

(2) In part by storage space for extreme high water reserved on top of the normal high water, within which space a sudden inflow can be retained until the sluiceways have time to discharge it down the stream,

(3) In part by a carefully worked out program of operation of gates and sluices, and their control by a small international committee, under whose orders sluices would be opened as soon as a high flood was predicted, and finally,

(4) **Safety can be secured with smaller range of surplus height after the enlargement of outlets of Lake Huron and Lake Erie, as hereinafter described.**

Also, it appears that Lake Erie in particular, and other lakes to less degree, can safely be held at higher elevations during midsummer, while navigation and the tourist season are at their height, than in the late autumn or early winter, for it is in October, or later, that the severe windstorms, which drive the water to unusual heights at one end of the lake, appear to have mostly occurred.

The recent studies of the late Professor J. F. Hayford upon the effects of winds and passing barometric waves upon Lake Levels, when somewhat further elaborated, promise to make it possible to exercise a more precise control of lake levels, by the aid of his formulas, than would have been possible heretofore.

Unified Control

A carefully worked out program for international control is essential to safety at maximum height, because once or twice in a century excessive rains may produce a run-off into anyone of the lakes so great that the existing natural channels would be insufficient in capacity to carry it off from a lake already full to the utmost limit, as fast as it might come in; although regulating gates were all wide open or non-existent. This has been carefully studied by reviewing the records of elevation month by month for the past sixty-five years and testing by computations, the capacity of the works now proposed for rendering all needed service in each emergency. It is to be expected that at some future time the narrow natural openings at the outlets of Lake Erie and Lake Huron will be enlarged, after which this margin of surplus height may be made smaller.

It is proposed that all of these gates and sluices controlling the levels and discharges of all the lakes, be worked in unison, so that in effect, water from Lake Superior can be immediately available to reinforce the level in Erie or Ontario.

It was largely because of failure to provide for unified control of all of the lakes simultaneously, that failure to give satisfactory service was indicated by the computations of the International Commission of 1910, which showed the unsatisfactory conditions liable to be imposed on Lake Ontario from the regulation of Lake Erie alone, unless Ontario was also provided with regulation works.

REGULATING THE DISCHARGE

Two kinds of regulation are to be considered. The preceding paragraphs have dealt with the problems of regulating the **elevation** of lake surfaces and holding these as high as practicable for the improvement of navigation. The second problem is that of regulating the **quantity discharged** so as to produce greater uniformity of flow, both for power and for navigation while also controlling the elevation within specified limits.

There are now wide variations in the rates of discharge of the lakes through the St. Clair, Niagara, and St. Lawrence Rivers, notwithstanding the remarkable natural regulation of run-off from this great drainage area provided in the natural rise and fall of storage over these vast areas. Under present natural conditions in winters of exceptional severity when large ice jams form, sometimes the average discharge for a whole month through the St. Clair River is only about one-half the average for the months of maximum discharge, and U. S. Assistant Engineer Louis C. Sabin, reports that on a certain occasion it was reduced by an ice gorge nearly to one-third of its normal delivery.

The average 24-hour flow in the Niagara River near the Falls varies in extreme cases between about 100,000 cubic feet per second to 300,000 cubic feet per second, under present natural conditions.

It is stated on page 45, paragraph 88, of the Warren Report that by means of a dam and gates at the outlet of Lake Erie and in co-operation with the regulation of Lake Ontario, it will be practicable to regulate the discharge of the Niagara River between say 180,000 and 200,000 cu. ft. per second. The details for this estimate were not published in the Warren Report, but its correctness is confirmed by the investigations made for the present report.

It is obvious that with gates at the outlets of each of the Great Lakes under unified control, better regulation can be had than by gates only at Lakes Erie and Superior. Computations will be presented in detail later, showing just what can be accomplished.

Because of the growing importance of water power development at Niagara and along the St. Lawrence, as well as at Sault Ste. Marie, it will become of increasing importance to utilize the storage capacity present in the rise and fall of the Great Lakes within predetermined limits to the greatest practicable extent; for **it is only by controlling the rise and fall of the lake surface that the regulation of discharge in the Niagara and St. Lawrence Rivers to greater uniformity in the future can be maintained.**

At present, the natural, uncertain and irregular holding back of water in storage by ice-jams in the St. Clair and Detroit Rivers, is sometimes more of a disturbance than a beneficent regulation, although in general, this holding back of water by ice in winter and its discharge in the navigation season, is helpful. Far better results can be had by intelligent unified control at the four great natural sluice-ways in the outlets of Superior, Huron, Erie and Ontario, than by leaving this regulation to Nature's vicissitudes of extreme cold, ice gorges, and heavy rains.

To bring about the best conditions for navigation without regard to helping water power development, would require that the lake always be constantly held at the highest practicable elevation without regard to storage. This would cause great irregularity in discharge, which would be injurious to water power development and would fail to provide the best conditions for the scenic beauty of Niagara Falls.

Navigation and water power development interests tend to look at this matter of regulation from diametrically opposite points of view. One of the chief problems is that of working out a just and reasonable compromise in the management of the regulation works, such that both navigation and power will share equitably in the benefits.

It is found that by means of the regulation works herein proposed, by holding the lakes always at the greatest heights consistent with regulating the discharge to a uniform flow of between 200,000 c.f.s. and 180,000 c.f.s. in the upper Niagara River, that the depths and elevations available for navigation without deepening channels by dredging, can be made to average 2 ft. greater than the average of the past 25 years.

Under regulation, by means of the works now proposed, the Great Lakes need never fall so low as to give less than 21 ft. clear depth* over lock sills at the Sault St. Marie and in the channels, all of the way from Duluth and Port Arthur to Buffalo and Tonawanda, instead of the 18 ft. recently prevailing.

The minimum mean monthly discharge of the Niagara and St. Lawrence Rivers can be increased by about 20,000 cubic feet per second upon the 310 feet fall, above that given by natural regulation, thereby adding about 526,000 horsepower of permanent water power in the ultimate development at Niagara, also adding about 384,000 horsepower in the ultimate development along the St. Lawrence under 226 feet fall; or a total of about 910,000 horsepower, can be added as one result of regulating the discharge.

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*Exclusive of effect of Earth-tilt.

SOME GENERAL DATA

That the reader may better understand the magnitude of the factors in this problem, the immediate presentation of some of the statistical data about the Great Lakes in the following tables may be useful.

Among their remarkable characteristics is the large proportion of the total drainage area of each lake comprised in the water surface. This causes differences, from year to year, in total depth of rainfall, and in total depth of evaporation, to both become uncommonly large factors in the water yield.

It is important to visualize the evaporation. Unfortunately, no satisfactory data have ever been obtained as to its precise amount, but careful estimates have been made from the best data available from various experimental tanks and reservoirs which indicate as follows.

During the three months, August, September and October, of nearly every year, evaporation takes out more water from the Great Lakes than the sum total of all that drains in meanwhile from tributary land areas, and during this time the discharge of the Niagara and St. Lawrence Rivers is mainly equivalent to what comes from storage in drawing down the elevation of the lake surfaces, plus whatever rain happens to fall on the lake surfaces.

For the entire year the rainfall on the water surface of the Great Lakes as a whole exceeds the probable evaporation by about 4 inches, but much of this rain falls outside the season of maximum rate of evaporation.

An annual evaporation of 27 inches in depth from this 95,160 sq. miles of water surface is equivalent to a constant flow of 188,000 cubic feet per second, while the average discharge from Lake Ontario into the St. Lawrence is about 248,000 cu. ft. sec.

In other words, the amount of water evaporated from the surface of the Great Lakes in course of the year is equal to about 76 per cent of the average discharge of the St. Lawrence River.

During the three months, August to October, it is probable that more water than the total which flows down the Niagara River goes off into the air from the surface of Erie and the lakes above it.

Observations upon the variation in depth evaporated from day to day, made at other reservoirs, indicate that possibly the evaporation from any one of the lakes may within a week or one day be at double the average rate, and on another day at only half the average rate, according to the temperature of air and water, and direction and dryness of the wind.

This variability from day to day implies variation from year to year and that this may be an important cause in the difference in net water yield from the Great Lakes system in different years.

DRAINAGE BASINS OF THE GREAT LAKES AREA IN SQUARE MILES

Name of Lake	Water Surface			Land Area			Total Land and Water		Grand Totals of Areas Both Land and Water	Per Cent. of Water Surface in Total Drainage	Ratio of Land to Water
	In U. S.	In Canada	Total Water	In U. S.	In Canada	Total Land	In U. S.	In Canada			
Superior	20,710	11,100	31,810	16,710	32,180	48,890	37,420	43,280	80,700	39.5	1.54
Michigan	22,400	0	22,400	46,640	0	46,640	69,040	0	69,040	32.4	2.08
Huron	9,110	13,900	23,010	15,880	33,710	49,590	24,990	47,610	72,600	31.7	2.15
Mich. & Huron	31,510	13,900	45,410	62,320	33,710	96,230	94,030	47,610	141,640	32.0	2.11
St. Clair	180	280	460	2,130	3,830	5,960	2,310	4,110	6,420	7.2	13.00
Erie	4,990	4,950	9,940	18,580	6,160	24,740	23,570	11,110	34,680	28.6	2.49
Ontario	3,560	3,980	7,540	15,160	11,940	27,100	18,720	15,920	34,640	21.8	3.59
Total All Lakes	60,950	34,210	95,160	115,100	87,820	202,920	176,050	122,030	298,080	32.0	2.13

Michigan and Huron form practically one lake.

The fact shown above, that for the lakes as a whole the water surface is about half as great as the net land surface, or in other words, that very nearly one-third of the entire drainage area is water, makes loss by evaporation and its variation from year to year a far more powerful factor here than it is ordinarily in storage reservoirs.

RANGE OF LAKE ELEVATIONS SINCE 1860

Name of Lake	Average Elevation 1860 to 1923	High Water of 1838	* Proposed Maximum Regulation Height	Margin of Safety Feet Height	Highest Monthly Averages in 65 Years 1860 to 1924	** Lowest Monthly Averages in 65 Years 1860 to 1924	Proposed Minimum Regulation Height	Proposed Storage Range Over Series of Years	*** Feet Gain in Minimum Depth for Navigation	Range High to Low Monthly Averages in 65 Years	Recent Monthly Averages Nov. 1925
Superior	602.27	605.32	604.5	0.8	604.08 Sept., 1869	600.54 April, 1911	602.0	2.5	1.0	3.54	601.11
Michigan	581.09	584.69	583.5	1.2	583.57 June, 1886	578.54 Jan., 1924	581.0	2.5	2.4	5.03	577.65
Huron	581.09	584.69	583.5	1.2	583.66 July, 1876	578.62 Jan., 1924	581.0	2.5	2.4	5.04	577.71
St. Clair	575.58	577.86	.....	..	......	......	....	..	..	....	573.06
Erie	572.49	575.11	574.5	0.6	574.52 June, 1876	570.63 Feb., 1902	573.0	1.5	2.3	3.89	570.45
Ontario	246.15	248.98	248.5	0.5	248.95 May, 1870	243.41 Nov., 1895	246.0	2.5	1.5	5.54	244.31

The elevations are in feet above mean sea level at New York.

The extreme stages for single days, cover a much wider range than the above extremes of monthly means.

*The Maximum Heights in Columns 1 and 2 do not include brief wind-effects or "Seiches" in which the cycle of oscillation is about 3 or 4 hours for Lakes Superior, Michigan and Huron, and is about 13 hours for the major cycles on Lake Erie.

**The present minimum height for a day, or sometimes the average height for a week, is much lower than this monthly average.

***The average effective depth gained for navigation would be slightly more than this 2.4 or 2.3 feet in Michigan, Huron and Erie, because each lake would normally be held by the regulation works at a high level for the longest time practicable during the navigation season, and would drop to the minimum height of the preceding column only near the end of long periods of deficient rainfall.

The gain month by month, for each lake, under conditions of the past 65 years, is shown in diagram, page 383. The comparison for the past 25 years is the best guide.

EXAMPLES OF EXTREME HIGH AND LOW ELEVATIONS OF LAKES RECORDED FROM 66 TO 105 YEARS AGO

A remarkably thorough compilation of water levels for the Great Lakes and St. Lawrence River prior to 1860, comprising several records of about 100 years ago, was compiled from all available authentic sources under the direction of Mr. L. E. Cooley, C. E. by Assistant Engineer J. Maloney, and presented as Exhibit B5 in the report of the Deep Waterways Commission for 1896-97; which comprised 23 closely printed pages, from page 169 to 192. This compilation apparently exhausted all sources of data from old records, and the work appears to have been done so carefully that there seems to be no need now of further search.

Readjustment is required, however, because of earth tilt, (unknown at the time of that report). After the precise position and direction of the several axes of earth tilt have been more thoroughly worked out, it will be advisable to review these old data and make proper adjustment, making further inquiry meanwhile as to the location of each old gage station.

Mr. Cooley and Mr. Maloney, after carefully reviewing the data, prepared "Deduced Tables" of gage heights for each lake, meanwhile recording their comments about some of the records of extreme high water and low water. Their researches appear to have justified the "High Water of 1838"* recorded on all U. S. Navigation charts, and these extreme high water levels from nearly a century ago down to 1860 also are of interest in considering possible flowage, but **correction for earth-tilt must be considered for all locations far from the outlet axis of the lake.**

From this research of 30 years ago, the following notes have been abstracted, for the purpose of showing that **cycles of changing water levels reaching just about as high and falling just about as low as any known in recent years, occurred about a century ago.**

No very old records for heights in Lake Superior were found.

The old low water records are of interest in showing that the recent conditions of extremely low levels are not unprecedented. Apparently, according to these records, nearly all of the Great Lakes about 100 years ago, or more than a half-century before the Chicago Canal was built, were drawn down to levels about the same as those of 1924 and 1925. The probable chief causes, then, as now, were deficiency of rainfall and excess of evaporation.

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*Replies to recent enquiry at the U. S. Lake Survey office indicate that exact data for "Highwater" of 1838 are few and vague; and that this record was not obtained for all of the lakes by actual observation or definite marks.

COMPARISON OF ANCIENT AND MODERN RECORDS OF EXTREME HIGH AND LOW LAKE LEVELS
ALL CORRECTED TO PRESENT LEVELS OF 1903

	LAKE SUPERIOR			LAKES MICH.-HURON			LAKE ST. CLAIR			LAKE ERIE			LAKE ONTARIO		
HIGH WATERS															
	MO.	ELEV.	STATION	MO.	ELEV.	STATION	MO.	ELEV.	STATION	MO.	ELEV.	STATION	MO.	ELEV.	STATION
1814 AND 1815				UN	USUALLY	HIGH	UN	USUALLY	HIGH				JULY 1815	247.10	AT MOUTH OF NIAGARA R.
1838 STANDARDS { BY OLD LEVELS 1876		604.76			584.34			577.62	DETROIT RIVER		575.20			249.04	MEAN FOR 1870
1838 STANDARDS { SAME BY NEW LEVELS 1903		**605.32**						**577.86**			**575.11**			**248.98**	
1838				JULY	584.69	MILWAUKEE	SUMMER	577.86	DETROIT R. WATER WKS.	JUNE 25TH	575.11	CLEVELAND	JULY	248.96	OSWEGO
							AUG	577.37	DETROIT R. WATER WKS				SEPT.	247.98	OSWEGO
1853							JULY	**576.79**	DETROIT R. WATER WKS.				JUNE	**248.46**	PORT DALHOUSIE
1858				NOV	584.00	CHICAGO	JUNE	577.71	DETROIT R. WATER WKS.	JUNE 19TH	575.36	CLEVELAND	JUNE	248.96	PORT DALHOUSIE
1859				JULY	584.04	CHICAGO	JULY	577.21	DETROIT R. WATER WKS.	APR.	574.84	CLEVELAND	JULY	248.99	PORT DALHOUSIE
EXTREME HIGH WATER RECORDED SINCE 1860.	SEPT 1869	604.08	MARQUETTE	JUNE 1886	583.57	MILWAUKEE	JULY 1876	577.74	ST. CLAIR FLATS	JUNE 1876	574.52	CLEVELAND	MAY 1870	248.95	OSWEGO
LOW WATERS															
1810 AND 1811 GENERAL											569.11				
1819				FEB	**578.02**	MILWAUKEE	MAR.	**571.19**	DETROIT R.	JUNE	**569.78**	BUFFALO	MAR	**243.52**	AT MOUTH OF NIAGARA R.
				JUNE	580.02	MILWAUKEE	JUNE	572.04	DETROIT R.	AUG.	569.36	BUFFALO	JUNE	245.94	AT MOUTH OF NIAGARA R.
1820				ABOUT SAME AS 1819			ABOUT SAME AS 1819			AUG.	570.07	CLEVELAND	MAR	243.02	AT MOUTH OF NIAGARA R.
1825										GENERAL LEVEL	571.11		MAR.	**242.44**	AT MOUTH OF NIAGARA R.
1841				DEC.	580.26	MILWAUKEE	OCT.	571.71	DETROIT R.	OCT.	570.64	CLEVELAND	DEC.	244.87	OSWEGO
1846				DEC.	579.66	MILWAUKEE				MAR.	570.64	CLEVELAND	MAR	244.21	AT MOUTH OF GENESEE R.
1847	MAR.	598.96	HEAD OF CANAL AT SAULT	FEB	579.19	MILWAUKEE				MAR.	571.23	CLEVELAND	JAN	245.21	AT MOUTH OF GENESEE R.
1848				MAR. 6TH	579.04	MILWAUKEE					570.89	CLEVELAND	NOV	244.21	OSWEGO
1853	MAY	598.88	HEAD OF CANAL AT SAULT												
1854		598.71	HEAD OF CANAL AT SAULT												
1857				JAN.	581.14	CHICAGO	JAN.	574.54	DETROIT R	JAN	571.74	CLEVELAND	JAN.	244.45	PORT DALHOUSIE
EXTREME LOW WATER RECORDED SINCE 1860.	MAR 1925	600.74	MARQUETTE	NOV. 1925	577.65	MILWAUKEE	NOV 1925	573.06	ST CLAIR FLATS	NOV 1925	570.45	CLEVELAND	NOV 1895	243.41	OSWEGO
LOW WATER OF 1925	MAR	**600.74**	MARQUETTE	NOV.	**577.65**	MILWAUKEE	NOV	**573.06**	ST CLAIR FLATS	NOV	**570.45**	CLEVELAND	NOV	**244.31**	OSWEGO

LOW RECORDS OF 50 TO 100 YEARS AGO REQUIRE CORRECTIONS FOR EARTH-TILT WHICH BRINGS THEM VERY NEARLY TO PRESENT LOW LEVELS.

As the figures stand in the tables, Lake Erie 105 years ago stood 1.14 feet lower than during 1925; but if this low level was measured at Cleveland the probable correction for earth tilt, amounting to 0.96 foot, would make the old height only 0.18 ft. lower than in 1925.

Lake Ontario, by the table, stood 1.87 feet lower 101 years ago than during the past year. This height was referred to Oswego, but the observations were at the mouth of the Niagara River from a series of observations once a month carried on for 12 years, 1815 to 1822, with much care by Mr. Edward Gidding of Lockport. Some uncertainty in correcting for earth-tilt attaches from failure to give details of date of reference to Oswego. The building of the Gut Dam across an outlet of Lake Ontario accounts for about 0.5 feet of the 1.87 feet leaving an apparent deficiency of 1.37 feet. The earth tilt for Ontario at Oswego would account for 1.58 feet if reckoned at 1.44 feet of tilt per 100 miles per century, from an axis W 17¾° N through the Galop's Rapids; making the water 0.21 foot higher than in 1925. Or if the tilt be figured at 0.63 foot per 100 miles per century, accounting for 0.70 foot, which the writer thinks may be enough here, the difference becomes 0.67 foot lower in 1925 than 101 years ago.

According to these records Lake Huron at the extreme low stage 105 years ago, stood 0.37 foot higher than in the year 1925, and a small part of this apparent lowering within 105 years is doubtless due to dredging and scour in the outlet channel. Compensation for earth tilt on a gage height measured at Milwaukee would account for 0.60 foot, but if the elevation was measured close to the outlet, little if any correction is needed.

The matter of position of each gage deserves further study and adjustment of observations to correct for the earth-tilt.

At the time of the Maloney-Cooley research the geographic position of the gage on the lake was regarded of no particular importance in determining its level.

The standard high water of 1838 also needs study, with its place of observation and with earth tilt in view.

Confirmation of all other authentic extreme highwater stages from every possible source of information now becomes of greater importance than ever before.

DISCHARGE FROM EACH LAKE

Measuring the discharge of the Great Lakes accurately is an extremely difficult problem and was not accomplished satisfactorily until about the time of the Deep Waterways Report of 1900.

A few complete gaugings in the St. Clair and Niagara Rivers, were made by Mr. D. Farrand Henry, in 1868 and 1869, who tried first the method of double floats, which he found more or less inaccurate and soon replaced by the method with a revolving wheel current meter. He secured results which happen to agree remarkably well with the elaborate measurements of 30 years later, notwithstanding that his instruments and methods were those of a pioneer, in an extremely difficult situation.

In 1898 to 1903, under Assistant Engineers E. E. Haskell, Mr. Francis C. Shenehon, Mr. Louis C. Sabin, and later Mr. Sherman Moore, the discharge of each of the Great Lakes was measured with newly devised apparatus (the Haskell current meter), and with such perfection of method that a precision of measurement was secured better than ever previously accomplished on any great river.

Apparently tradition, or habit, in precision of measurement had been developed on the triangulation and surveys of the Great Lakes under General Comstock, which these exceptionally able assistant engineers sought to import into the field of measurement of river discharge.

DISCHARGE FROM LAKE ERIE

The diagram on the following page, which is typical of diagrams of discharge in terms of lake height made for each lake, gives the final results of many measurements of the discharge of the Niagara River, taken at three different measuring stations, each having a different shape of cross section, and different mean velocities, in order to guard against inaccuracy that might be caused by turbulences of water or eddies at the first station tried, which was at the International Bridge.

The positions and shapes of these several measurement sections are shown in the map on page 256. The close agreement secured in measurements at sections so different in their characteristics of shapes and velocity is most remarkable.

Each measurement of discharge is plotted against the elevation of Lake Erie, which was observed continuously during the progress of each measurement. It will be noted that the quantity being discharged bears a very definite relation to the height in the lake, and since the discharge is through an unchanging channel in bed rock, knowing the height in the lake on any particular date, although 50 years prior to the time of these velocity gagings, the discharge, for that particular height, can be taken off the mean line of this diagram.

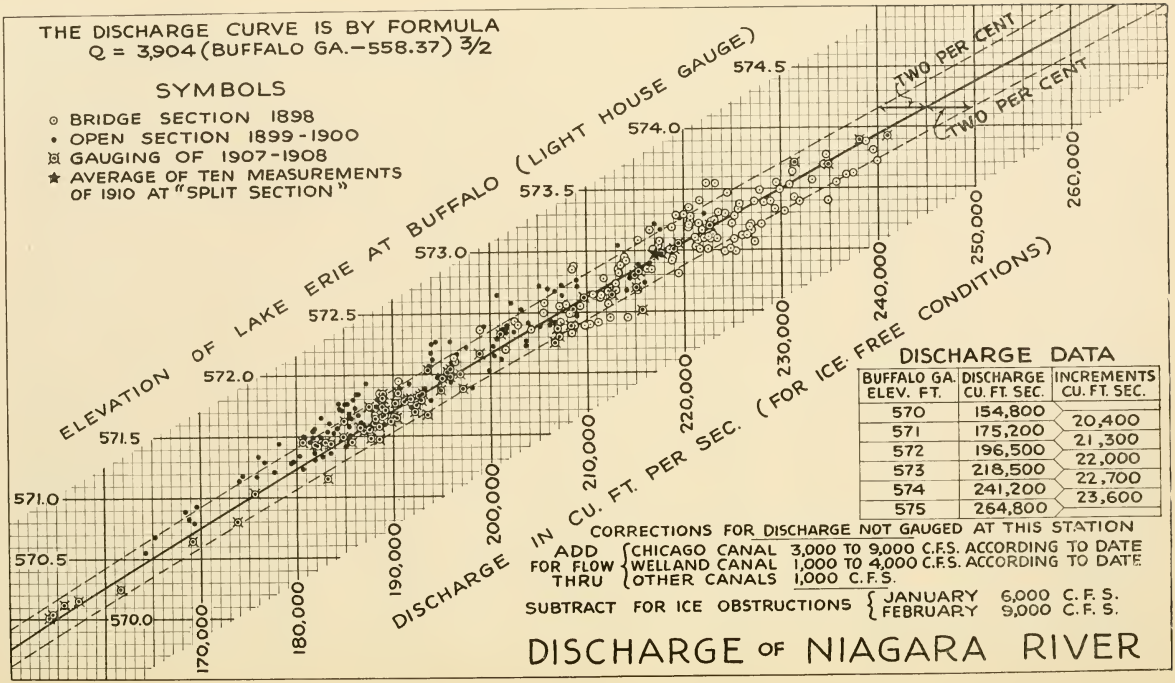
The precision of measurement shown by the close agreement of the quantities plotted on this diagram, few of which fall so much as 2 per cent away from the mean line, has never been equalled elsewhere in the measurement of a great river. This accuracy is fortunate because it is on these measurements that our estimates upon regulating the discharge of all the lakes above Niagara depend.

In the case of the Niagara River, by means of rating curves or formulas established by these gagings, made between 1898 and 1903, the discharge can be determined with excellent accuracy **under ice-free conditions** in past, present and future times, so long as no important obstructions or changes take place within the head of the river.

For the purposes of the present report, one is not greatly concerned with the degree of precision or accuracy achieved in the measurements of discharge from Lake Superior or from Lake Ontario, because Lake Superior is already regulated, and Lake Ontario is the particular concern of the International Commission now studying the St. Lawrence.

The establishing of an accurate formula or diagram for giving the discharge of the St. Clair River in terms of the records of height in Lake Huron appears to have involved special difficulties, and while the final averaged results are sufficiently accurate for the purposes of this report, many individual measurements in the St. Clair and Detroit Rivers are open to question, and at times perhaps 5% to 10% in error.

The occasional obstruction of lake outlets by ice prevents the precise application of these formulas or diagrams throughout the winter, and this will be discussed on a later page.



BUFFALO GA. ELEV. FT.	DISCHARGE CU. FT. SEC.	INCREMENTS CU. FT. SEC.
570	154,800	20,400
571	175,200	21,300
572	196,500	22,000
573	218,500	22,700
574	241,200	23,600
575	264,800	

DISCHARGE DIAGRAMS FOR LAKES MICHIGAN AND HURON

These two lakes have such a broad and deep connection in the Straits of Mackinac that there is no opportunity for separate measurement of their discharge, and both have to be considered as one lake.

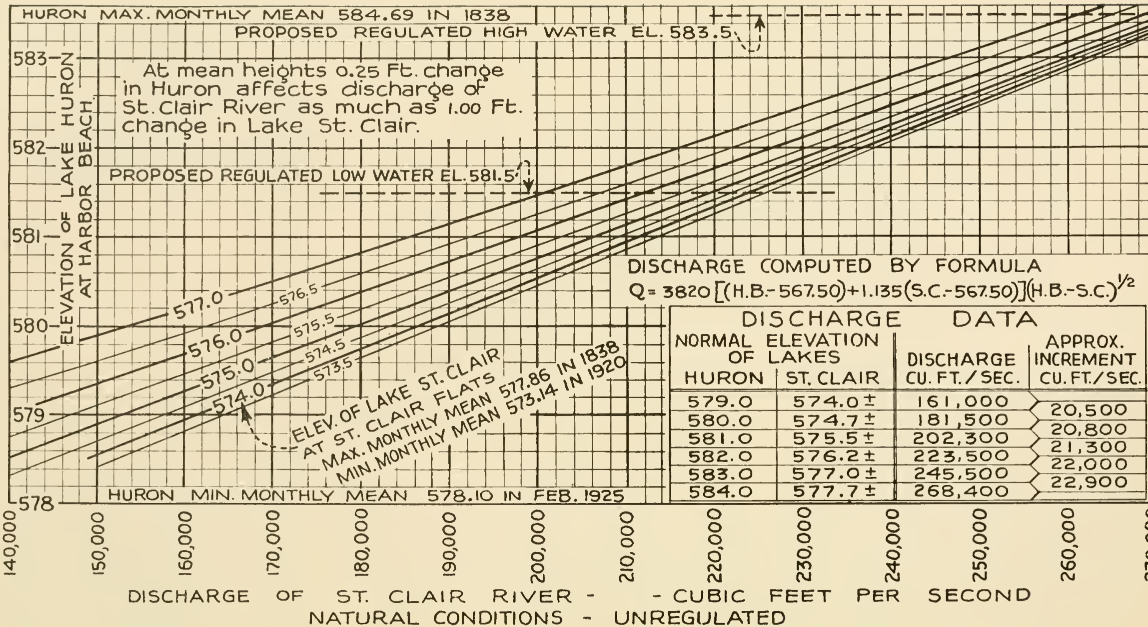
Many discharge measurements by means of Haskell current meters have been made, in both the St. Clair and Detroit Rivers, and at several different points in the St. Clair River, without attaining the precision and certainty of measurement obtained at the outlet of Lake Erie. Below the outlet of Lake Huron there is no suitable section which is surely permanent in regimen because of having rock bottom all of the way across. Moreoever, the small amount of fall downstream from the narrow controlling section near the outlet from the lake is somewhat unfavorable, and instead of the oscillations of one lake there are those of two lakes to disturb the hydraulic relations, one or both often changing rapidly. Moreover, the obstruction by ice is much more severe in both the St. Clair and Detroit Rivers than in Niagara.

At first the Engineers of the Lake Survey tried to get a satisfactory formula for the discharge of the St. Clair River in terms of the elevation of Lake Huron only. Later it was found that better agreement between different measurements could be had by including also the elevation of Lake St. Clair as a factor. Two discharge diagrams are presented on following pages, the first based on the relation of Huron and St. Clair, the second diagram uses Lake Erie as the modifying factor. The diagram on page 212, utilizes the elevation of Huron alone, assuming that the relative elevation of Lake St. Clair is normal.

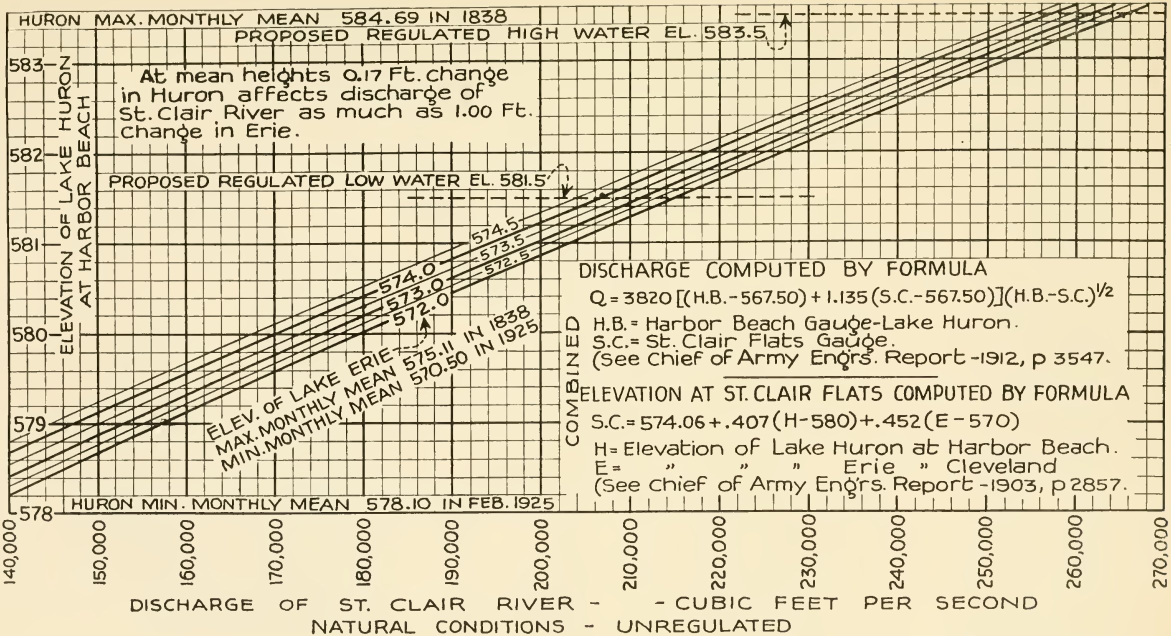
Formulas have been derived from measurements in the Detroit River, based on elevations in Lake St. Clair and Lake Erie, and were used for computing the tables of discharge in the Report on Regulation of Lake Erie in 1910.

Series of gagings have been several times repeated after a long interval, to make certain about change of regimen of the St. Clair river bed, which, being over clay and gravel, is possibly subject to scour.

Gagings in the St. Clair River are now taken as the standard, rather than gagings in the Detroit River, which were used for the estimates of the International Waterways Commission in their report of 1910. A discharge diagram for the Detroit River is given on page 34.



CURVES OF DISCHARGE OF ST. CLAIR RIVER FOR VARIOUS ELEVATIONS OF LAKES HURON AND ST. CLAIR



CURVES OF DISCHARGE OF ST. CLAIR RIVER FOR VARIOUS ELEVATIONS OF LAKES HURON AND ERIE

LAKE SUPERIOR DISCHARGE

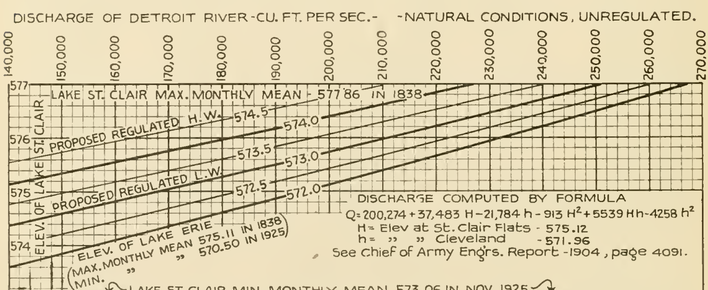
No discharge diagram for Lake Superior is presented here, because of the changed relations since regulating gates have been constructed entirely across the St. Marys River, adjacent to the locks. Moreover, the varying draft for power at the industrial plants and hydroelectric stations at the Sault has changed conditions so that heights in Lake Superior are only one of the lesser factors that control the discharge.

DISCHARGE OF THE DETROIT RIVER

Various formulas for discharge, based on the elevations of Lake St. Clair and Erie, have been derived from gagings made during the summers of 1901 and 1902, although no formula has been derived for the winter discharge when the river may be partially blocked with ice.

The table of values of discharge of Detroit River, 1860–1907, given in the Report of the International Waterways Commission, 1910, are derived from a different formula than that given in the diagram below.

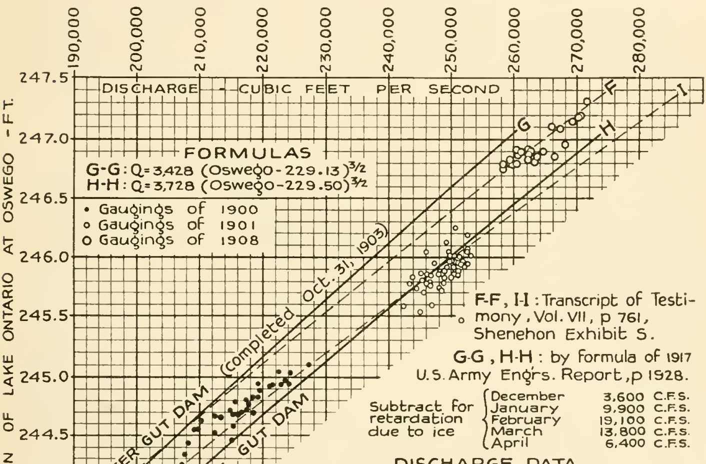
Although at that time it was thought that the computed discharge of the Detroit River was a better measure of the outflow from Lake Huron, after applying a constant value for yield of Lake St. Clair, it appears from more recent discharge measurements in the St. Clair River and after applying new formulas for computing the discharge through the St. Clair River based on the elevations of Lake Huron and Lake St. Clair, that a more accurate result can be had from the St. Clair River formulas than from the Detroit River formulas.



At mean height, 0.58 Ft. change in Lake St. Clair affects discharge of Detroit River as much as 1.00 Ft. change in Lake Erie.

CURVES OF DISCHARGE OF DETROIT RIVER
FOR VARIOUS ELEVATIONS OF LAKES ST. CLAIR AND ERIE

The relation of discharge of the St. Lawrence River to elevation of Lake Ontario was changed about the year 1903, by the construction of a dam across the head of one of the three channels at the head of the Galops Rapids, about 6 miles downstream from Ogdensburg, for the purpose of increasing the depth and removing objectionable cross currents near the entrance to the Canadian Galops Rapids Canal. One result of this was to increase the elevation of Lake Ontario very nearly 0.50 ft., as is shown by the diagram below.



DISCHARGE DATA

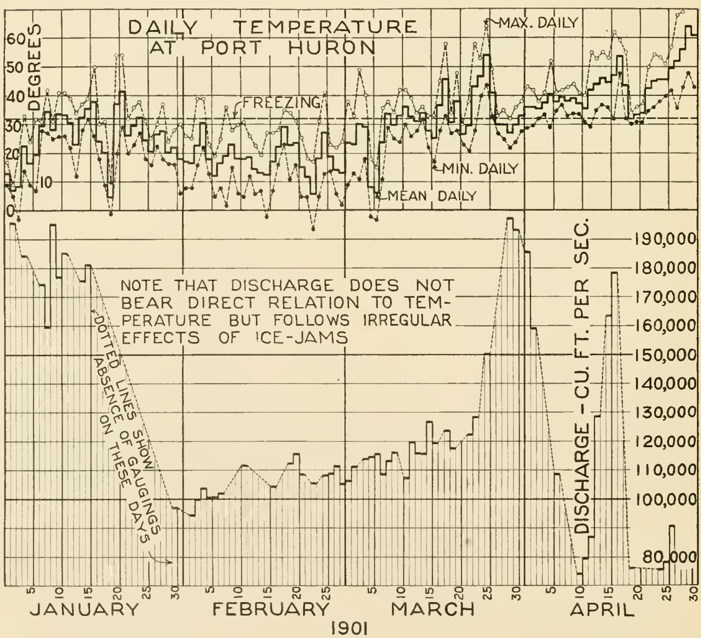
OSWEGO GAGE ELEV FEET	BEFORE GUT DAM DISCHARGE C.F.S	INCREMENT C.F.S.	AFTER GUT DAM DISCHARGE C.F.S.	INCREMENT C.F.S.	CORRESPONDING ELEV. AT OGDENSBURG - FT.
248.	296,640	23,720	280,990	22,040	246.94
247.	272,920	23,060	258,950	21,420	245.99
246.	249,860	22,360	237,530	20,810	245.05
245.	227,500	21,660	216,720	20,160	244.11
244.	205,840	20,930	196,560	19,490	243.16
243.	184,910		177,070		242.22

DISCHARGE OF ST. LAWRENCE RIVER AT OUTLET OF LAKE ONTARIO

CORRECTION FOR OBSTRUCTION BY ICE

The obstruction of these lake outlets by ice to a degree that varies greatly from week to week and from year to year, makes the winter discharge uncertain for a varying number of days each winter. In the earlier records there is little from which to estimate the amount by which discharge was lessened by ice, and figures for discharge in early reports must be used with caution, for in many cases no allowance for ice was made, and therefore the recorded discharges are too large, particularly for Lake Huron. This in turn makes the apparent yield contributed by Lake Erie drainage area too small in the early records.

A few direct measurements of flow in the St. Clair River while it was obstructed by ice were made in 1901, and the effect of ice on the discharge is shown by the following diagram. A few measurements were made on the Niagara River during the winter of 1898.



ICE EFFECT ON DISCHARGE OF ST. CLAIR RIVER IN A WINTER OF EXCEPTIONAL SEVERITY

There appear to never have been any observations systematically recorded from year to year for the purpose of estimating the winter discharge accurately, by making proper reduction from the quantity as shown by the formulas derived from gagings made in summer, to allow for the retarding effect of ice.

The estimates for obstruction by ice presented by Mr. Richmond in the Warren Report have been accepted as being the best available at the present time. These corrections in cubic feet per second, for the outlet of each lake, are given in the following table.

The values adopted provisionally in 1903 by the Army Engineers in charge of the Lake Survey office, are presented in a parallel column, and a comparison of these two values of ice correction for Lake Huron illustrates the degree of uncertainty.

Approximate Average Corrections for Obstruction of Discharge by Ice.

	Lake Superior	Lake Huron	Lake Huron	Lake Erie	Lake Ontario
Reference to page in Warren Report	Page 360 cu. ft. sec.	Page 362 cu. ft. sec. (Richmond)	Used by Army Engineers Prior 1903	Page 363 cu. ft. sec.	Page 364 cu. ft. sec.
December	———	6,200	8,600	———	3,600
January	average 2,800 (January–March)	27,500	47,750	6,000*	9,900
February		42,500	60,833	9,000*	19,100
March		28,000	55,700	———	13,800
April	———	14,100	39,550	———	6,400 (April–May)
May	———	1,500	11,000	———	
Total	8,400	120,000	217,433	15,000	52,800
Average for whole 12 months	700	10,000	18,120	1,250*	4,400

*These Lake Erie figures are from Mr. Shenehon. Mr. Richmond adopts 3 per cent. for three months as the amount by which the Lake Erie outflow is lessened by ice, equivalent to 1,500 c.f.s. for the year instead of 1,250.

Mr. E. E. Haskell, long connected with the Lake Survey office, has told the writer, that one who has studied the river a long time and is familiar with its peculiarities, can obtain an excellent idea of the amount of obstruction at any time by a close study of the daily charts from the recording gages.

Assistant Engineer Thomas Russell gave this matter much attention and made a report that is published with the Chief of Engineers Report of 1904. Assistant Engineer Sabin also has given this matter much study. All of these studies were available to Mr. Richmond in his Review of 1922.

On page 52, Report of 1911, on Preservation of Niagara Falls, Mr. Shenehon says: "Lake Ontario is raised an average of 7 inches annually by ice checking the flow, and Lakes Michigan and Huron in some years nearly as much."

AVERAGE DISCHARGE FROM EACH LAKE

It is a matter of such vital importance to get this basic data on the discharge into and out from each lake, with all practicable accuracy, that members of this committee have reviewed the data anew and have applied corrections while using the recorded discharges month by month for the past 25 years, or the past 65 years, as a basis for estimating the limits between which the discharge can be regulated.

Tentatively the following figures were adopted for normal average mean discharge, in cubic feet per second, for the 65 years, 1860 to 1924. (Differences between these and other estimates will be discussed on a later page.)

					Yield in Cubic Feet per Second per Square Mile	
	Outflow Uncorrected for Ice	Outflow Corrected for Ice	Also Corrected for Diversion	Also Corrected for Rise and Fall of Lake	Land and Water	Land Only
St. Marys River	77,170	76,470	76,470	76,020	0.943	1.560
St. Clair River	191,740	181,740	184,340	181,400	0.820	1.255
Niagara River	207,280	206,030	211,100	207,900	0.789	1.183
Head of St. Lawrence River	248,700	246,800	249,410	245,600	0.822	1.210

The first column gives the discharge computed from lake elevation. The second column gives the average of **quantities actually found flowing,** after allowing approximately for obstructions by ice, without taking account of diversions. In the third column the quantities diverted by Chicago, Welland and Erie Canals are added. The final column gives the average water yield into each lake, including the yield into all lakes lying upstream. The drafts for power at the Soo and at Niagara Falls are included in all of these figures.

The figures in the fourth column all are smaller than in the third column to the extent measured by the amount by which each lake surface is now lower than in 1860, distributed into the 65 years. The difference between yield and discharge, due adjustment for rise or fall, from any one year to the next is commonly much larger than that between the third and fourth columns.

The separate yields for the individual lakes are found by subtraction to be as follows, after correction for ice, diversions, and rise or fall:

	Total Net Yield	Per Sq. Mi. Total	Per Sq. Mi. Land Only
Lake Superior	76,020 c.f.s.	0.943	1.560
Lakes Michigan and Huron	105,380 c.f.s.	0.745	1.085
Lakes St. Clair and Erie	26,500 c.f.s.	0.644	0.864
Lake Ontario	37,700 c.f.s.	1.088	1.390
Total, as before	245,600 c.f.s.	0.822	1.210

The small yield per square mile from Lake Erie doubtless is due to its large evaporation.

Curiously, the yield per square mile of the respective lakes and their drainage areas, is in inverse ratio to the rainfall which they receive, probably because of the more southern exposure of the lower lakes, their larger tillage and their greater loss by evaporation.

RAINFALL AROUND GREAT LAKES

So much has been said attributing recent low lake levels to diversion by the Chicago canal, that it has seemed worth while to go into these matters of rainfall, run-off and evaporation with some detail and to put the main facts on record and try to bring plainly into view the ways in which climatic changes control lake levels.

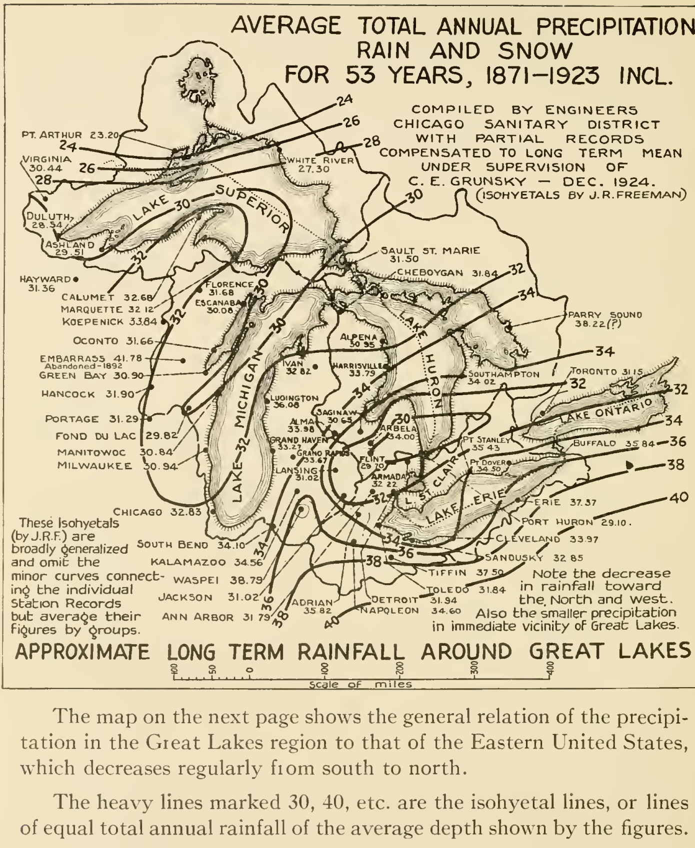
In the Chief of Engineers Report of 1903, pages 2859–60, are given average values for rainfall around the Great Lakes determined at a great number of stations which are indicated on a map of the region. Some stations had been observed for a much longer period than others. Details of methods used in making up the weighted average are not stated.

A new collection of rainfall data was prepared in the office of the Sanitary District in October and November, 1924, at the request of Mr. Grunsky of the Lake Levels Committee, in which particular attention was given to adjustment of the weighted average, by first selecting about 55 of the stations having the longest records, dividing these into 13 geographic groups and computing for each station year by year the ratio of the precipitation in each year to the long term mean. Where there were gaps in the record for any station, interpolations were made from adjacent stations and by means of this ratio. Finally the average precipitation at each station, and for each group, was determined for the same term of 53 years, 1871 to 1923 inclusive. These values have been plotted on the map shown on the next page, and isohyetals, or contours of equal rainfall, drawn. In two or three cases the records for one station were so out of relation to that of all adjacent stations that they were given little weight in drawing these isohyetal lines.

Doubtless a somewhat more precise diagram could be prepared by taking more time and by investigating the quality of observations at each station so as to explain a few anomalous records, and by also including many of the short term records of volunteer observers, and compensating each series, according to the general ratio of precipitation year by year during this short term, to that of the 53-year term; but the differences from the curves now presented certainly would be small and of no importance in the present discussion.

The average values determined by planimeter from the above map for each lake separately for land area, water area, and for both combined are given in the table on page 42 following the maps.

Note that the larger part of the drainage area tributary to Lakes Superior and Huron lies on the northern, or Canadian side. The precise figures in square miles are given on page 25.



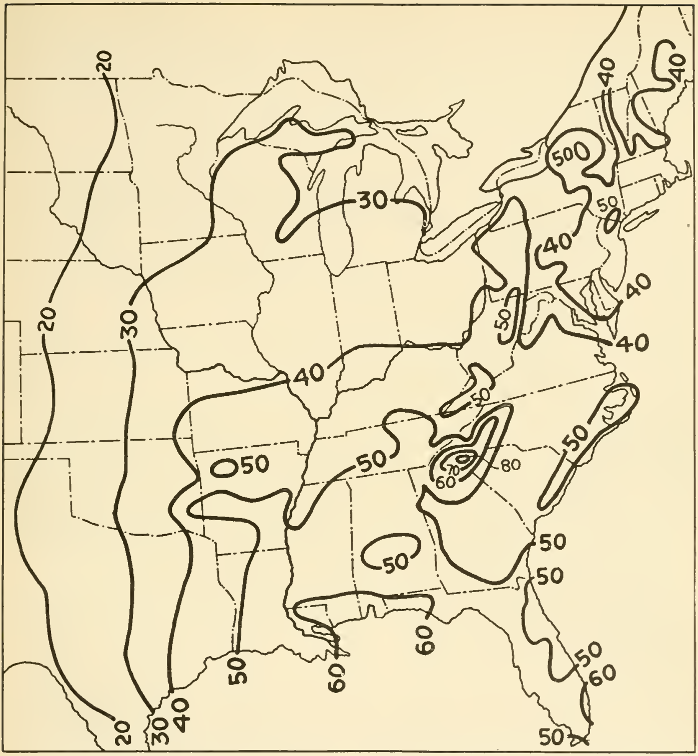
The map on the next page shows the general relation of the precipitation in the Great Lakes region to that of the Eastern United States, which decreases regularly from south to north.

The heavy lines marked 30, 40, etc. are the isohyetal lines, or lines of equal total annual rainfall of the average depth shown by the figures.

Records of rainfall upon islands near the Straits of Mackinac and in the western end of Lake Erie, not shown on the above map, also have been considered. These are as follows:

	Inches
Mackinac Island, (Lake Huron) 25 years, 1900–1924, average not compensated	32.80
Compensated to long term average by Alpena group	36.80
Weighted average of 6 nearest gages on shore for 53 year term Sault St. Marie, Cheyboygan, Escanaba, Alpena, Ivan, Harrisville	31.80
Put in Bay (Lake Erie) 9 years, 1916–1924, uncomp. 30.00,	Compensated 30.6
North Bass Island (Lake Erie) 15 years, 1869–74, 1916–1924, uncomp. 27.2	Compensated 28.4
Catawba Island (Lake Erie) 9 years, 1916–1924, uncomp. 29.00,	Compensated 29.6
Kelley's Island (Lake Erie) 14 years, 1859–1871, 1916 uncomp. 31.74,	Compensated 30.8
Mean of four islands in Lake Erie	Compensated 29.9
Mean of Toledo, Tefin, Sandusky, Detroit, nearest stations on shore for 53-year long term	33.7

Comparing records on adjacent islands, year by year, large differences are noted.



NORMAL ANNUAL RAINFALL OVER THE EASTERN UNITED STATES

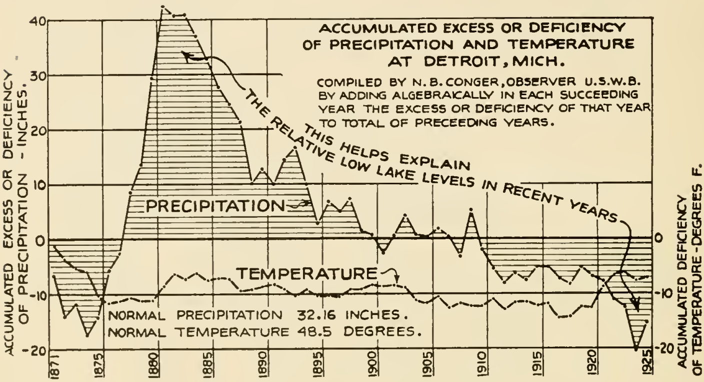
From Miami Conservancy District Technical Reports, Part V

LONG TERM AVERAGE ANNUAL RAINFALL ON GREAT LAKE DRAINAGE

Lake	Per Cent of Water Surface in Drainage	Long term aver. annual rainfall, according to above map and its lines of equal rainfall, average for 53 years on			Normal rainfall for Whole Land and Water Area as Computed by Engineers Sanitary District for 53 Years	Average rainfall (1882–1898) per U. S. Chief of Engineers Report, 1903 17 Years	Average rainfall (1876-1925) per Canadian Meteorological Service, 50 years	Probable Evaporation From each Lake Surface *
		Water Area Only	Land Area Only	Total Area Land and Water				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Superior	39.5	28.9	27.2	27.9	28.19	26.27	28.8	22.0
Michigan-Huron	32.0	31.8	32.2	32.1	33.40	32.21	33.4	27.5
Erie, St. Clair	25.3	34.3	34.5	34.4	34.31	34.08	34.4	36.0
Ontario	21.8	32.3	33.7	33.4	....	36.87	33.0	33.0

*These estimates of evaporation are approximate. See page 164. They are included here for comparison with rainfall and indicate that on all of the lake surfaces evaporation is nearly as large as the rainfall, and on Lake Erie exceeds it.

The following diagram shows how much less the rainfall has been in recent years, than that of 40 years ago. That this is no evidence of permanent climatic change is shown by the high and low lake levels of a hundred years ago on page 27.



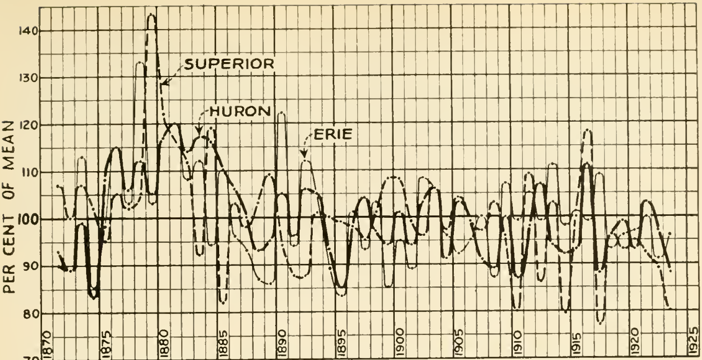
There are presented in parallel columns of the preceding table two other series of average rainfall values for comparison and as illustrating the margin of uncertainty.

The fifth column of values as computed by the engineers of the Sanitary District was derived from substantially the same data as the values on the map on page 40, by grouping and combining weighted averages.

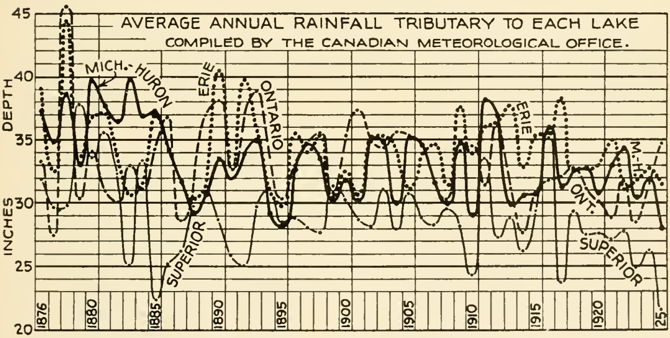
The sixth column presents values worked out for a much shorter term. The discrepancies between the fifth and sixth column appear large until one reviews the sheets showing variations of 25% or 30% at the same station from year to year, and some remarkable variations in total annual rainfall at places but a few miles apart, in the same year.

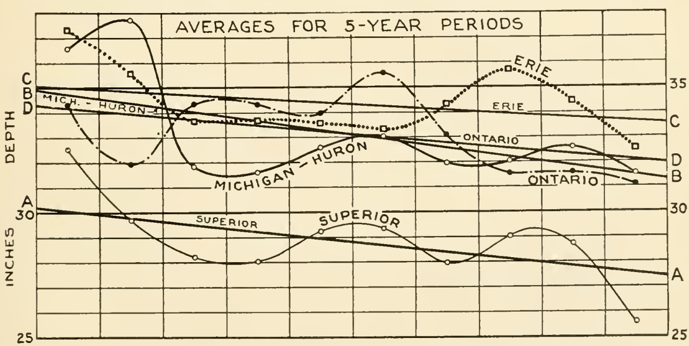
The seventh column is from a study made by the Canadian Meteorological Service.

The following diagram is made up from the data compiled by the writer. Perhaps its most interesting feature is the apparent diminution of precipitation (rainfall) shown by drawing a thread across from left to right. This shows a lessening of rainfall in about 50 years, from about 8% above to about 8% below the long term mean.



RATIO OF ANNUAL RAINFALL TO LONG TERM MEAN ON EACH DRAINAGE AREA





Note the tendency to a gradual decrease in precipitation shown by the "Average Lines" A-A, B-B, C-C and D-D.

Approximately at the rate of—2.8 inches in 50 yrs. on	Superior	(A-A)
3.6 " " " " "	Mich.-Huron	(B-B)
1.5 " " " " "	Erie	(C-C)
2.3 " " " " "	Ontario	(D-D)
Equivalent to a weighted average of 3.0 " " " " "	All lakes	

(See other diagrams in Appendix No. 4.)

The two lower diagrams on the previous page are from an independent estimate by the Canadian Meteorological Service. **Both of these diagrams concur with the Conger diagram on page 42, in showing a remarkable decrease in rainfall in recent years, to which the recent low lake levels are largely due.**

The evident return from similar low lake levels of about a hundred years ago, noted on page 27, gives good reason for believing that this decrease is not permanent, but is only the downward swing of a cycle covering many years in which an upward swing may be expected soon.

(See diagrams on larger scale in Appendix No. 4.)

COMPARATIVE RAINFALL ON LAKES AND ON LAND

The isohyetal lines for the Great Lakes region shown on page 40 were drawn so as to give weight to an apparent diminution of rainfall over the lakes observed at a few stations in and around Lakes Michigan, Erie and Ontario, with the result that by planimetering the areas between these lines the comparative depths are found as follows:

	Superior	Mich.-Huron	Erie	Ontario
Mean rainall over land	27.2	32.2	34.5	33.7
Mean rainfall over water	28.9	31.8	34.3	32.3

There have been observations of rainfall on a few islands in the lakes which show less rainfall than at the nearest shore stations, but the observations available for measuring precisely whatever difference there may be between precipitation on land and on water appear too few to be broadly conclusive. Differences greater than those shown above have often been found in the records from rain gages on land in close proximity to each other, due to the differences of exposure of gage to wind currents.

ADDITIONAL NOTES ON RAIN GAGES, RAINFALL, RUN-OFF AND FOREST INFLUENCES

The ordinary rain gage is not an instrument of precision and seldom is the record accompanied by proper information about the exposure of the gage.

In Appendix No. 4 there are presented additional notes and data upon the accuracy of rain gage records in general which show:

1. Exposure to strong winds may diminish the rain caught by 10% or more. Elevation of the gage above the surface of the ground generally gives greater wind effect and thus increases this under-registry.
2. In a location exposed to strong winds, a gage of nearly double the diameter of the standard 8 inch pattern of the U. S. Weather Bureau, will catch slightly more rain, and one smaller than this standard will catch slightly less.
3. If the larger rainfalls of a year happen to occur in summer when crops and trees are growing rapidly, the percent of yield from these large rainfalls will be smaller. The rain falling in the smaller storms nearly all evaporates so that very little of it reaches the rivers or lakes.
4. Cycles of rainfall observations extending back 150 years indicate there has been no important "permanent" change.
5. The observations of the past 65 years indicate a slight but well defined decrease of rainfall during this period.
6. The water loss, or difference found between the total annual rainfall and the total discharge at the outlet of each lake is found wonderfully constant from year to year. This gives confidence in the measurements of both rain and run-off.
7. The records of 65 years around the Great Lakes Superior, Michigan-Huron and Erie show no measurable effect upon water-loss, or run-off which can with any certainty be traced due to the rapid cutting off of the pine forests between 1870 and 1890.
8. There was a change in water-loss on the Ontario drainage about 1890 for which no good reason is evident.

RELATION OF RUN-OFF TO RAINFALL

On page 38 attention has been called to the curious fact that the **water-yield** of the individual lakes and the drainage areas directly appurtenant to each, is in **inverse ratio to the rainfall received** upon each; that while Lake Superior receives the smallest total annual rainfall, it delivers the largest water yield per square mile of total area and per square mile of land, and that although Lake Erie receives 6.5 inches, or 23.3%, more rain, it delivers little more than half as many cubic feet per second per square mile.

The above suggests abnormal conditions of evaporation from lake and from land in each case, working in opposite directions and which are worthy of further investigation. The table below analyses and compares the rainfall on each separate drainage system in inches depth, and in per cent delivered at outlet.

	Drainage Areas			Aver. Total Annual Rainfall Inches Depth	Aver. Water Yield cu. ft. sec. Corrected	Aver. Total Annual Run-off Inches Depth		Per Cent. of Run-off to Rainfall	
	Total Sq. Mi.	Land Only	Water Only			On Total Drainage Area	From Land Area Alone *	On Total Drainage Area	From Land Area Alone *
Lake Superior	80,700	48,890	31,810	27.9	76,020	10.66	13.07	38.2	48.0
Lakes Huron and Michigan	141,640	96,230	45,410	32.1	105,380	8.41	10.30	26.2	32.0
Lakes St. Clair and Erie	41,100	30,700	10,400	34.4	26,500	7.30	10.40	21.2	30.1
Lake Ontario	34,640	27,100	7,540	33.4	24,340	7.95	10.34	23.8	30.7

*These values represent the run-off from the land area alone after taking into consideration the evaporation from the land, as given in the table below, and the evaporation from the water surface as given in the table at bottom of page 41, column 8.

It is of interest to compare these depths of run-off as measured at the lake outlets, with the depths of run-off gauged on the inflowing rivers presented on later pages.

LOSS OF WATER FROM LAND DRAINAGE

Due to Evaporation, Transpiration, etc.

The table below gives the probable total average yearly losses of water from the land areas of each lake for the 65 years, 1860 to 1924. The quantities evaporated from the water surfaces of the lakes, as given in table on page 41 and the values of total depths of run-off from the whole drainage areas, given in the table above, were used to obtain the following results.

TOTAL AVERAGE YEARLY LOSS OF WATER FROM THE LAND DRAINAGE OF EACH GREAT LAKE. INCHES DEPTH ON DRAINAGE AREA

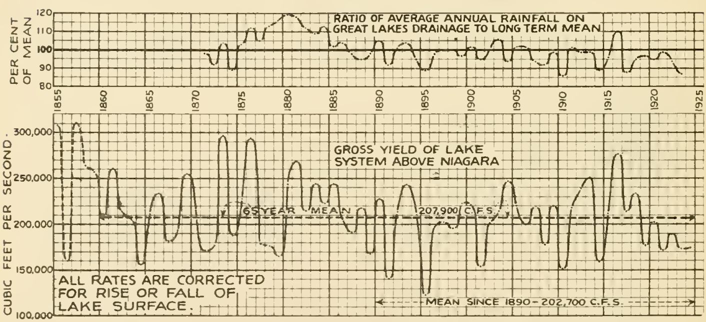
Superior	Michigan-Huron	Erie, St. Clair	Ontario
14.13	21.90	24.10	23.36

VARIATION IN ANNUAL RAINFALL AND RUN-OFF

The diagram, page 43, of rainfall ratios shows that these values for the separate drainage areas around different lakes do not fall closely into line with one another year by year, but that there is a general agreement.

Combining the yearly ratios of rainfall for all of the lakes into a single line in the upper part of the following diagram, a general agreement is found in the rainfall ratio year by year with the total rate of water yield above Niagara. The agreement of these two lines, of rainfall ratio and of water yield, do not run so nearly parallel as one might at first expect, but upon examination into these variations, becomes plain that the total annual rainfall is but one of many factors, and that **the ratio of annual rainfall by itself is found to be an uncertain index to the run-off of any one of the Great Lakes in any particular year.**

A study, month by month, is presented on later pages.



RELATION OF TOTAL WATER YIELD ABOVE NIAGARA TO AVERAGE ANNUAL RAINFALL

There are many circumstances which confuse the issue. Although whatever rain falls upon the lake surface is a net gain, the run-off from the land surface into the lake during a calendar year depends quite as much upon the concentration of rainfall and upon the time of year in which it falls, as upon its total depth for the year. In other words, a monthly total of five inches of rainfall concentrated mainly in one or two storms will produce a far greater run-off than the same total precipitation if given in many small storms or showers.

During the summer the rain falling in small amounts, while vegetation is in active growth, mostly evaporates before reaching the streams which enter the Great Lakes from the south.

Around Lake Superior and north of Huron, the cooler air, the larger proportion of forest cover and of less absorbant earth surface, may conserve a larger proportion of the rain that falls on the land area, so that it reaches the rivers and lakes.

In the southern part of the Great Lakes drainage area a large portion of the land is under cultivation and the transpiration from its vegetation in summer is large. Moreover, nearly all of this topography has a gentle slope, tending to a sluggish run-off and to increased evaporation.

Lack of concurrence between the rainfall ratio and the water yield measured into the lakes year by year, may in part result from the slow rate of travel of the percolating water under ground toward the lake; because the land surface within these drainage areas is largely a deposit of glacial sands and gravel which, when not frozen, absorbs the rainfall with more than common facilitity and tends to conserve it from escape while it is slowly percolating toward the main stream beds and into the lakes, so that a considerable portion may take several years in its underground transit, thereby carrying a part of the rainfall of one year into the run-off of a later year.

This relation of run-off to rainfall is discussed in much more detail on later pages.

NEGATIVE WATER YIELD OF LAKES

The several Great Lakes vary in their water yield from year to year, and from month to month, more than is shown by the fluctuation in the measurements of discharge described in detail on later pages. Their enormous area and the rise and fall of surface equalizes to a large degree the natural fluctuations of yield from tributary streams into the lakes, and in tracing back the causes of some of the curious relations of rainfall to run-off already referred to, it was found that after adjustment was made for rise and fall of lake level, **both Lake Superior and Lake Erie show a negative yield for several months in nearly all years.** That on Superior occurs at about mid-winter, and that on Erie in the late summer and autumn. In each case large evaporation is a chief cause.

In other words, on Lake Superior during the winter months, or ordinarily from about the middle of December to the middle of March, when streams mostly are more or less ice-bound and direct precipitation onto the lake is not large, **the evaporation loss from the vast surface of Lake Superior exceeds the inflow continuously during about three months.**

This points to a depth of evaporation during the winter months, far greater than that reported in text book data, and was one reason for the following extended study of evaporation from the Great Lakes, and for the attempt to estimate it by various methods, which follow. Also it was hoped that this ultimate study would help in explaining the causes of the lowering of the Great Lakes in recent years.

Prior to this extended study reported on pages 65 to 149 an estimate is presented, covering the past 25 years (during which time the gauge heights and estimates of discharge are most dependable), of the monthly yield into each lake, as found after correcting the discharge from each lake down the St. Marys, St. Clair, Niagara and St. Lawrence Rivers, first for probable obstruction by ice, second for diversions and third for total rise or fall of lake level during each month of the year.

A copy of this computation, which was carried through 25 years, is given for a single year, for Lakes Superior and Erie, as a sample to illustrate the method of computation and the amount of the compensation for water yield corresponding to rise or fall of lake surface.

Sample Estimate of Net Water Yield from Lake Superior Drainage Area for Year 1924

(Outflow computed from gage height, corrected for ice and rise or fall of Lake Surface.)

Date, Year and Month	Estimated Monthly Outflow Through St. Marys River	Add or Subtract for Rise or Fall of Lake Superior		Deduct for Obstruction of Flow Due to Ice	Computed Total Net Yield of Lake Superior Drainage
		Feet	Equivalent c.f.s.		
1924					
January	50,210	—.13	— 43,850	2,800	+ 3,560
February	50,040	—.31	—104,500	2,800	— 57,260
March	51,300	—.23	— 77,600	2,800	— 29,100
April	52,060	—.05	— 16,900	0	+ 35,100
May	53,160	+.13	+ 43,850	0	+ 97,010
June	50,160	+.09	+ 30,350	0	+ 80,510
July	46,580	+.09	+ 30,350	0	+ 76,930
August	50,400	+.26	+ 87,800	0	+138,200
September	49,170	+.22	+ 74,250	0	+123,420
October	49,680	+.04	+ 13,500	0	+ 63,180
November	51,230	—.13	— 43,850	0	+ 7,380
December	49,910	—.29	— 97,900	0	— 47,990
Average	50,330	—.025	— 8,720	700	+ 40,910

Sample Estimate Net Water Yield from Combined Drainage Areas of Lakes Erie and St. Clair for Year 1924

Outflow, computed from gage height, corrected for ice and rise or fall of lake surface, plus diversions less computed inflow from Lake Huron

Date, Year and Month	Discharge through St. Clair River, as Computed from Elevation of Huron and St. Clair	Discharge Through Niagara River, as Computed from Elevation at Buffalo	Deduct for Ice Retardation in Niagara River	*Add for Diversions Through Erie and Welland Canals	Add or Subtract for Rise or Fall of Lake Erie		Total Correction to Apply to Discharge of Niagara River	Total Corrected Outflow from Lake Erie	Computed Total Net Yield from Lake Erie and St. Clair Watershed
					Feet	Equivalent c.f.s.			
1924									
Jan.	130,000	193,800	6,000	5,000	+.02	+ 2,200	+ 1,200	195,000	+ 65,000
Feb.	98,000	175,500	9,000	5,000	+.04	+ 4,400	+ 400	175,800	+ 77,900
Mar.	145,000	174,800	0	5,000	—.09	—10,000	— 5,000	169,800	+ 24,800
April	151,600	185,700	0	5,000	+.55	+61,100	+66,100	251,800	+100,200
May	162,200	196,700	0	5,000	+.39	+43,300	+48,300	245,000	+ 82,800
June	165,100	199,900	0	5,000	+.14	+15,600	+20,600	220,500	+ 55,400
July	167,200	204,500	0	5,000	+.14	+15,600	+20,600	225,100	+ 57,900
Aug.	171,400	197,500	0	5,000	—.29	—32,200	—27,200	170,300	— 1,100
Sept.	171,200	191,800	0	5,000	—.20	—22,200	—17,200	174,600	+ 3,400
Oct.	163,300	187,200	0	5,000	—.25	—27,800	—22,800	164,400	+ 1,100
Nov.	160,100	184,800	0	5,000	—.64	—71,100	—66,100	118,700	— 41,400
Dec.	144,000	182,200	0	5,000	—.28	—31,100	—26,100	156,100	+ 12,100
Aver.	152,400	189,500	1,250	5,000	—.04	— 4,350	— 600	188,900	+ 36,500

*Note that the diversion through the Chicago Canal affects the discharge from both Lakes Huron and Erie equally and therefore is not included in this computation.

The results of similar computations, month by month, for 25 years for each of the Great Lakes are given in the following tables.

The **minus signs show the months of negative yield,** in which evaporation exceeded the inflow from all local tributaries plus rainfall on lake surface.

NET YIELD FROM LAKE SUPERIOR DRAINAGE

In hundreds of cubic feet per second.
Corrected for rise or fall of lake surface.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Aver.
1900	—487	127	— 50	383	1336	984	1566	2076	2690	1221	852	—429	856
1901	—413	—290	— 26	495	1738	1126	2488	1337	267	886	547	—357	650
1902	—576	—119	72	779	1736	1710	1554	790	909	345	755	— 78	656
1903	—528	—292	230	1258	2357	2062	1474	1184	871	1254	64	—543	783
1904	—319	137	274	502	1774	1835	1155	1174	1318	1514	472	—533	775
1905	—159	—469	338	1452	1609	1433	1891	1315	1635	970	351	136	875
1906	— 15	—239	7	522	1930	1870	1291	984	951	495	239	85	677
1907	— 61	139	230	711	1268	2310	1352	1670	1736	818	— 33	—356	815
1908	—729	—109	119	312	2033	2616	1823	1122	351	214	— 410	— 64	606
1909	—373	—201	135	333	1704	1756	1545	1564	825	432	633	794	762
1910	—161	—279	—188	975	1057	1196	656	1038	708	592	— 124	—296	432
1911	—622	—124	—314	96	1482	2079	1772	2210	921	617	104	133	696
1912	61	—261	165	611	2112	1640	1140	1280	1086	522	145	—156	696
1913	—457	—494	354	1054	2123	1666	1651	1207	914	1418	285	127	821
1914	—335	10	—354	368	2009	1498	1467	981	985	617	— 72	—514	555
1915	—274	203	—110	128	1674	1766	1881	1148	894	1864	1037	322	877
1916	370	23	—216	1382	2923	2577	1565	1353	1574	615	518	19	1058
1917	—406	—359	601	660	1255	1450	1174	1059	855	476	103	—422	537
1918	—206	—324	127	311	1403	2102	1020	985	1208	416	939	314	691
1919	—121	—140	—106	899	1222	1343	874	586	453	145	695	158	501
1920	—440	58	460	1663	1146	1816	1583	1000	274	156	— 24	—225	622
1921	—139	—501	15	1038	1656	1434	1145	911	559	— 21	— 498	—360	436
1922	—722	—295	— 91	1151	2058	1150	1446	951	667	— 208	— 194	—329	466
1923	—361	—112	14	241	1193	775	1267	936	689	366	118	— 44	424
1924	36	—573	—291	351	970	805	769	1382	1234	632	74	—480	409
25-Yr. Aver.	—298	—179	56	707	1671	1640	1422	1210	983	654	263	—124	667

NET YIELD FROM LOCAL DRAINAGE OF LAKES HURON AND MICHIGAN

In hundreds of cubic feet per second.

Obtained by deducting the mean quantity gaged flowing in St. Marys River from that flowing in the St. Clair River, corrected for ice, for diversions by Chicago Sanitary Canal and for rise or fall of lakes.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Aver.
1900	— 20	1184	1384	1647	2226	1618	1620	1912	819	1074	375	—525	1109
1901	—250	163	2732	1198	3256	1502	1650	1434	230	— 528	— 424	—318	886
1902	—266	41	2306	1529	3104	2212	2819	1338	—619	395	581	—234	1100
1903	—368	1473	2036	2543	1644	2039	2049	691	1574	380	— 609	—650	1066
1904	1001	652	2117	3356	3051	3141	1356	787	912	582	— 277	—576	1342
1905	—333	—120	1613	3076	2500	3197	1975	1151	784	— 944	— 150	330	1090
1906	1017	1277	1585	2066	2560	1867	1322	1096	—495	236	352	743	1135
1907	632	646	1373	2570	2115	3084	1358	878	1127	8	— 840	603	1129
1908	—214	891	1430	2840	4129	2084	2268	778	—853	— 518	—1982	498	946
1909	—104	1178	1258	2591	3894	2358	1192	1330	—106	—1174	628	821	1156
1910	—449	793	1572	3005	1933	1614	812	416	958	232	— 406	—588	824
1911	—531	1680	388	2498	2569	2662	500	1072	684	671	— 218	1644	1135
1912	—297	877	1268	1970	3778	3302	1651	1793	1712	— 147	1322	121	1445
1913	458	5	2502	4668	2857	2029	1427	1378	— 35	159	— 264	490	1306
1914	—167	701	574	2025	2220	2617	2010	768	222	458	—1642	—388	786
1915	56	1864	426	789	1923	1880	1505	2193	120	204	— 659	718	918
1916	—275	1284	1279	3410	3734	3983	2071	—157	—967	8	1605	401	1365
1917	152	389	1726	2833	2783	3434	3019	1232	499	— 161	467	—918	1288
1918	862	1165	2547	2456	2897	2801	1698	1172	—264	64	898	1848	1513
1919	—232	1138	1938	3100	3124	2284	490	395	—186	1024	176	—478	1064
1920	62	835	1883	3289	2520	1822	2022	1208	382	— 233	67	279	1178
1921	425	474	1747	3664	2365	1653	582	— 77	603	540	446	435	1071
1922	—132	733	2417	3982	3812	2042	2092	1110	495	— 580	— 744	—953	1188
1923	729	—698	2059	2277	3325	2273	1600	470	802	— 85	— 319	—309	1010
1924	—338	1692	951	2240	2614	2011	1687	1976	743	25	—1322	—469	984
25-Yr. Aver.	57	814	1644	2625	2837	2380	1631	1038	366	68	— 118	101	1121

NET YIELD FROM LOCAL DRAINAGE OF LAKES ERIE AND ST. CLAIR

In hundreds of cubic feet per second,
after deducting discharge of St. Clair River.
Corrected for ice, diversions and rise or fall of its surface.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Aver.
1900	417	667	1087	645	420	325	25	92	—314	— 305	— 302	— 18	228
1901	78	286	262	1090	— 77	355	126	—281	—142	— 499	— 255	156	93
1902	430	—169	388	723	497	384	913	150	—218	137	— 115	— 22	258
1903	586	653	1012	1216	367	266	200	— 46	— 32	— 281	— 440	15	293
1904	178	512	1236	1631	513	464	81	—210	—186	— 331	— 366	—221	275
1905	477	584	150	714	771	689	240	—112	—197	— 288	— 376	206	238
1906	161	590	107	552	278	229	44	4	—300	— 95	78	619	189
1907	932	583	116	667	345	609	195	—195	—217	25	— 132	45	248
1908	1210	493	957	1001	554	208	— 87	— 95	—422	— 349	— 522	—184	230
1909	226	781	985	530	1190	582	13	— 49	—366	— 520	— 61	27	278
1910	438	206	710	636	823	281	— 3	— 13	— 76	30	— 292	257	252
1911	260	579	179	817	539	249	— 16	— 20	46	193	— 154	633	275
1912	512	235	546	1567	705	315	112	119	175	— 258	— 72	—234	310
1913	983	913	554	2274	389	246	— 19	—158	—413	— 244	6	112	387
1914	312	34	235	985	1131	443	3	—100	— 99	— 141	— 466	190	211
1915	405	636	585	248	441	389	462	578	150	19	— 289	222	321
1916	775	1100	727	1027	790	788	173	—280	—472	— 338	— 217	— 44	337
1917	452	— 50	327	1314	625	832	599	—149	—205	— 310	328	50	318
1918	93	23	1069	839	—260	253	— 58	—120	—110	— 184	— 146	81	123
1919	125	145	511	873	990	398	—117	— 98	—221	— 138	— 60	5	201
1920	244	— 52	216	816	800	316	276	96	—175	— 231	— 30	278	213
1921	213	708	522	1089	638	222	157	—150	— 90	— 270	249	320	301
1922	372	151	466	1390	750	430	95	— 83	— 23	— 289	— 310	—118	236
1923	514	316	521	818	597	438	207	—141	— 56	— 168	— 138	697	300
1924	650	779	248	1002	828	554	579	— 11	34	11	— 414	121	365
25-Yr. Aver.	442	428	549	980	566	411	168	— 51	— 157	— 193	— 180	128	258

NET YIELD FROM LAKE ONTARIO DRAINAGE

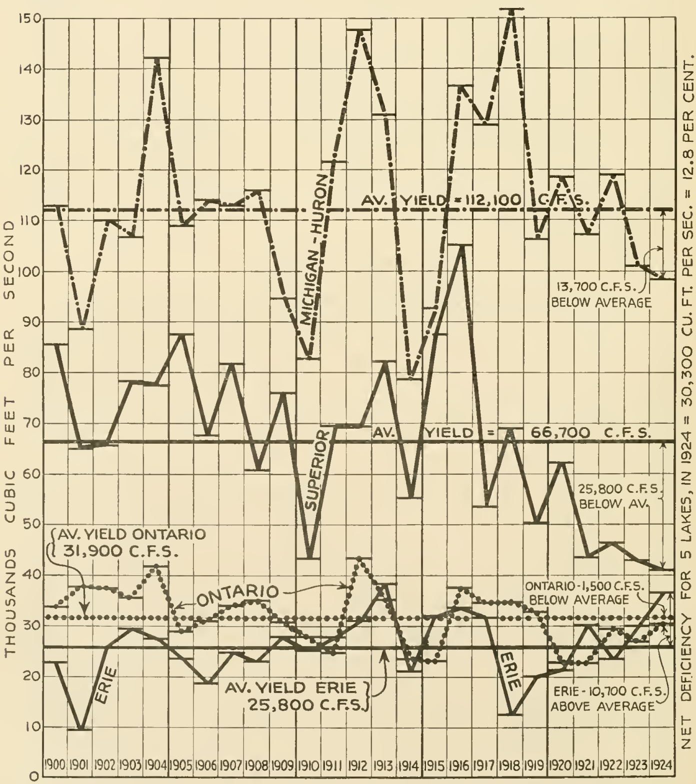
In hundreds of cubic feet per second.
After deducting discharge from Niagara River, Erie and Welland Canals.
Corrected for ice and rise or fall of its surface.

Year	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Aver.
1900....	460	477	443	851	581	330	298	108	— 44	— 33	80	515	338
1901....	250	367	123	1519	883	631	269	181	99	— 57	— 42	294	376
1902....	323	107	921	833	494	455	671	498	0	95	— 35	139	374
1903....	299	539	826	953	509	271	506	230	165	39	— 15	— 33	358
1904....	— 26	538	716	1440	939	656	488	282	144	124	— 25	—259	419
1905....	185	— 21	— 70	1092	441	558	612	271	225	86	21	90	290
1906....	573	425	219	652	479	393	511	68	— 95	— 15	273	260	311
1907....	590	359	289	700	606	375	318	167	— 19	204	230	270	340
1908....	482	495	621	772	940	752	378	248	—175	—125	—101	— 64	351
1909....	19	320	591	750	1219	526	274	123	— 68	— 35	— 82	72	309
1910....	38	318	905	509	689	378	212	158	62	— 1	74	12	280
1911....	154	386	336	746	456	381	213	26	42	3	3	275	251
1912....	239	279	347	1274	849	962	231	120	133	189	236	359	435
1913....	705	547	273	1239	489	474	273	8	— 35	12	108	105	350
1914....	42	428	29	1274	573	336	217	30	144	—104	— 49	—113	233
1915....	199	501	519	157	388	223	194	436	239	— 43	— 25	23	234
1916....	361	468	180	1072	1007	1098	598	34	—118	—157	— 17	— 7	376
1917....	172	148	244	1163	493	634	664	233	— 18	78	311	34	346
1918....	68	208	848	1039	556	403	306	34	117	151	268	196	349
1919....	445	202	362	603	990	989	297	62	4	— 58	93	— 40	329
1920....	— 12	165	355	800	308	171	297	140	85	48	155	269	230
1921....	414	259	609	786	565	269	89	— 84	—197	— 41	16	75	230
1922....	113	199	587	1082	758	529	568	126	— 69	— 27	—104	—207	296
1923....	155	265	381	771	564	605	264	10	5	— 29	— 2	269	272
1924....	401	350	278	700	958	520	277	221	22	177	—140	—106	304
25-Yr. Aver.	266	333	437	911	669	517	361	149	26	19	54	97	319

The following diagram shows the total net yield into each lake for each year, and is based upon the foregoing tables. It is of interest to note the relatively small net annual yields of Lakes Erie and Ontario, as compared with Michigan-Huron or Superior; and also it is of interest to compare this diagram of yield into each lake, with that of the discharge from each lake on page 235.

It is of particular interest to note how largely the yield of Lake Superior, and also of Lakes Michigan-Huron, has fallen off in the past four years in comparison with that of 8 or 10 years previous. This shows the chief cause of the lowering of the Great Lakes.

Holding up the level of Lake Superior by partially closing the regulating gates, **has lessened the elevation of the other lakes which have no gates to hold them up.** With the regulation works now proposed, all of the Great Lakes could have been held up to normal heights.

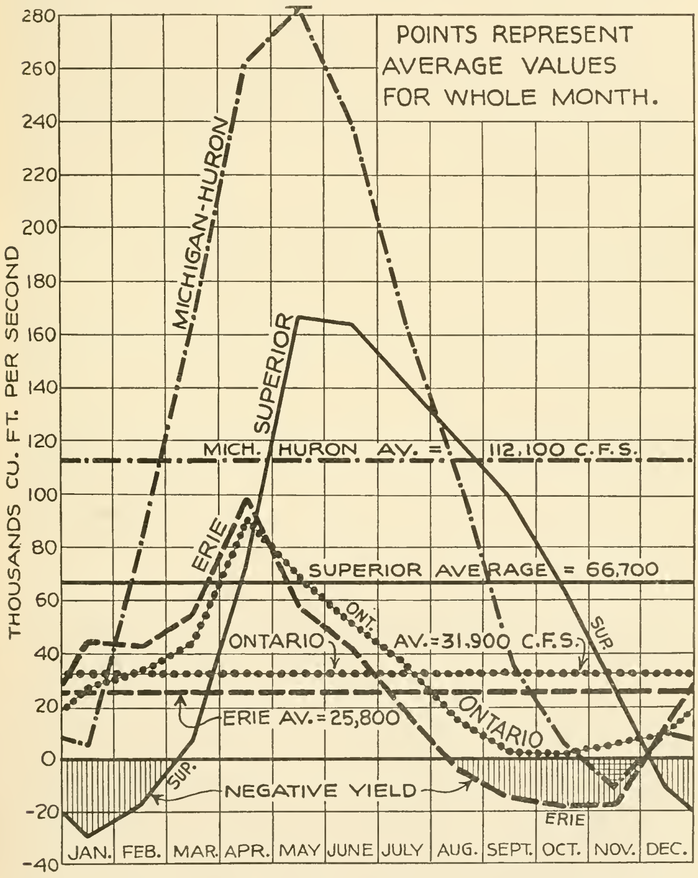


NET ANNUAL WATER YIELD FROM LOCAL DRAINAGE OF EACH LAKE—AV. CU. FT. PER SEC.

From Discharge, corrected for Diversions + ice + rise or fall of lake surface.

The following diagram also is based upon the preceding tables, and shows the average yield of each lake, month by month, during the past 25 years. It brings out conspicuously the fact of negative yield.

The negative yield of Superior comes in mid-winter, that of Lake Erie in the late summer and autumn. Lake Michigan-Huron also gives a negative yield in November. **All of these negative yields are due to excessive evaporation.**



NET MONTHLY WATER YIELD FROM LOCAL DRAINAGE OF EACH LAKE FOR 25 YEAR PERIOD, 1900–1924

From discharge corrected for ice, diversions, and rise or fall of surface. (Exclusive of discharge from Great Lake next upstream.)

This includes all inflow from local tributaries, plus rainfall on surface, less evaporation.

Now that the fact of abnormal evaporation from the Great Lakes as compared with ordinary reservoirs has been shown, and a reasonable correction made for the effect of ice in lessening the discharge estimated from gaugings made in summer, no reason is found for doubting the substantial accuracy of gaugings of discharge from Lake Erie, which has been questioned in past years.

It can no longer be doubted that during periods of several months duration, **there is more water evaporated from Lake Erie than flows into it from all of its local tributaries, so that Lake Erie delivers into the Niagara River day after day a smaller quantity than it receives from the Detroit River.** Meanwhile, its outflow is maintained in large part by the expenditure of storage previously accumulated, thereby lowering its level.

Nor can it be doubted that Lake Superior has a small evaporation loss in summer, and a remarkably large evaporation loss in winter, **from its open surface,** which all through January and February takes out more water than comes in from all of its tributaries.

Open water at 32 degrees Fahrenheit is warm in comparison with winter winds at temperatures of zero or below which prevail on many days of winter at this latitude.

In April, May and June the solar heat that falls on Lake Superior is largely absorbed in melting the vast quantities of minute ice crystals and in an effort to raise the temperature of water at maximum density (temperature at 39°F.) brought from the great depths by action of wind and by the meeting or obstructions by currents caused by barometric waves.

EFFECT OF TEMPERATURE ON LAKE LEVELS AND DISCHARGE DUE TO EXPANSION AND CONTRACTION

The expansion and contraction of the water in the Great Lakes, due to temperature changes from winter to summer and the reverse change, has not been included in any of the estimates of yield or evaporation. Below a depth of 100 feet little change in temperature takes place, water remaining almost constantly at 39.1° F., the temperature of maximum density. The temperature gradient from this depth to the surface will vary irregularly from winter to summer. Because of lack of precise information, assume an average change of 12 degrees in temperature of water 100 feet deep, equal to ⅓ the difference between the maximum density, or deep-water, temperature of 39.1° F. and a maximum surface temperature of 75° F., then, since the expansion and contraction must all take place vertically, the effect in raising or lowering the water surface of one of these Great Lakes would be about 0.031 foot, or about ⅓ of an inch from summer to winter.

This is equivalent to an increase or a decrease of about 650 c.f.s. in the rate of discharge. The differences in height and discharge are less than errors of observation in elevation and discharge and will balance out in the long run.

RUN-OFF MEASURED IN TRIBUTARY STREAMS

For tracing back to their causes the low lake levels of recent years and the alternating cycles of high lake levels and low lake levels, a study of the variations in the measured run-off from tributary streams into the lakes (outside the rivers connecting the lakes), gives a far better line of evidence than does a study of the records of the total amount of rainfall from year to year. Because as stated on page 46, the proportion of the rain which reaches the lake, or the river, is extremely variable, no distinction is made in the annual total between the rainfall of half an inch, nearly all of which is evaporated before reaching the stream, or the precipitation of several inches in a short storm, on frozen ground, 75% of which may reach the stream.

Systematic stream gaging is a recent institution, and unfortunately the run-offs in these tributaries have been measured and recorded only for a very small part of the 65 or more years for which the lake levels have been recorded, and in general these stream-flow measurements do not present a satisfactory record throughout the whole year.

The actual gagings of winter flow of these tributary streams by current meter, or other precise means, have been infrequent; and many of the records of winter discharge, being estimated from gage height, are of uncertain value because of the influence of ice cover and ice jams upon stream flow, and because of the complete freezing up of many small brooks in exceptionally severe weather.

Nevertheless, the reports of tributary stream measurements by the U. S. Geological Survey have been reviewed and apparently reliable data extracted, which are presented in the following tables. The unit of measurement adopted, is total inches in depth of annual run-off on drainage area, in order that comparison may be more readily made between total annual depth of rainfall and total run-off, year by year.

In Canada, systematic measurements of stream flow were begun more recently than in the United States, so that only very few years of records are available for the streams entering the lakes on the Canadian side. The actual run-off for the climatic year 1921–22 for each of the important Canadian streams is shown on the map on page 15, in terms of inches total depth on drainage area. This map shows the location of many of the principal tributaries, and the table which follows on page 64, gives the record for each, year by year, back as far as found published. Recent data have been supplied from the Canadian Water Resources Branch, Department of the Interior.

These Canadian run-offs agree in a general way in their variations from year to year with those measured on the American side.

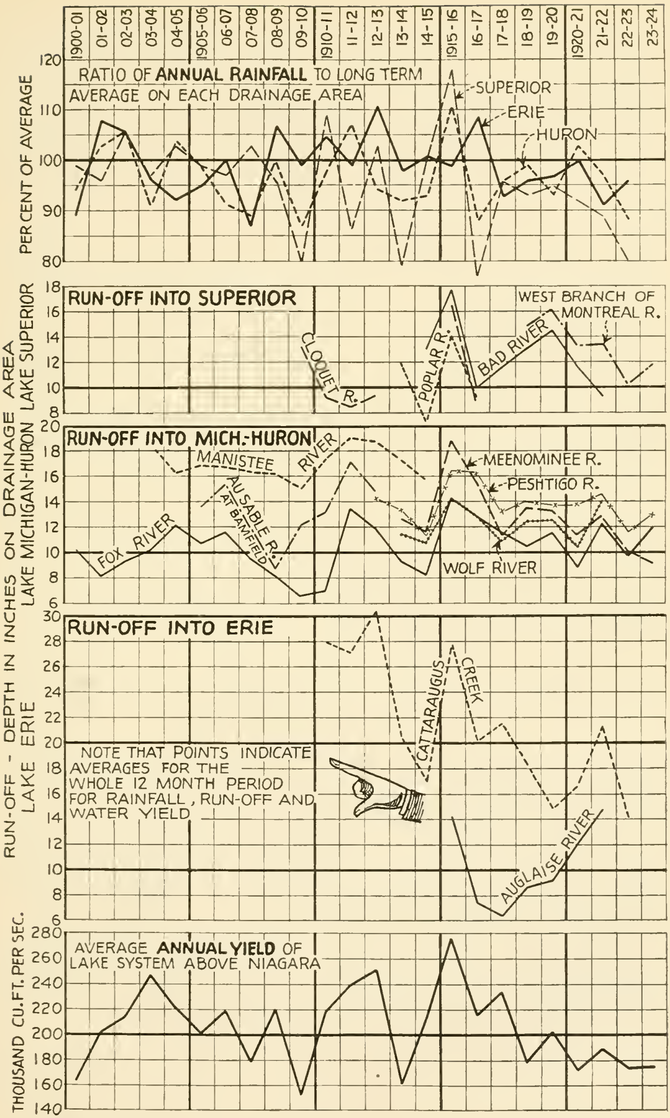
It is understood that the Canadian hydrographers have given particular attention to measuring the winter discharge, because the motive for much of their hydrographic work has been the estimate of resources for future power development, in which the winter discharge is a highly important feature.

Comparing these figures, many differences are found between the yearly depths of run-off of individual tributaries, dependent largely upon the characteristics of the different water sheds whether forest covered or open, steep with rapid run-off, or flat and absorptive, etc., but in some cases the scatter of observations is doubtless caused by lack of precision in gaging the discharge.

In a general way the fluctuation of lake levels reflects the fluctuations found in these total annual depths of run-off, but the parallel between rise or fall of lake and increase or diminution of inflow is far from precise.

The comparison in detail year by year that follows, serves to show up the diversity of the factors which control the water yields of more than a hundred tributaries, that are summed up, averaged and smoothed out, in the total yearly run-off into each Great Lake.

In the diagram on the next page, values for the yearly depth of run-off, for several of the most prominent rivers tributary to each of the Great Lakes above Niagara, on the United States side, have been plotted, together with curves showing the annual variations in rainfall on each lake, and the average annual net yield of the lake system above Niagara, in order to bring out more clearly the lack of concurrence between rainfall, run-off into the individual lakes, and the net yield from the lakes. The long-term average rainfall on each drainage area, on which the annual ratios in the following diagram are based, is for the calendar years 1871 to 1923 inclusive.



COMPARISONS OF RAINFALL, RUN-OFF AND WATER YIELD INTO GREAT LAKES

RELATION OF RUN-OFF TO RAINFALL

Preparatory to the computations of the following tables, and after noting apparent inconsistencies in depths of runoff from year to year given in the preceding diagram for adjacent streams, a brief examination was made with a view to excluding doubtful data, by comparing, for each of the principal streams, the ratio of depth of run-off to depth of rainfall from year to year. The result is shown in the diagrams that follow.

In each of these a curve has been drawn in the general direction which this ratio should follow if conditions were alike in the different years. It is seen that the observations scatter and show no strong tendencies to follow such a curve.

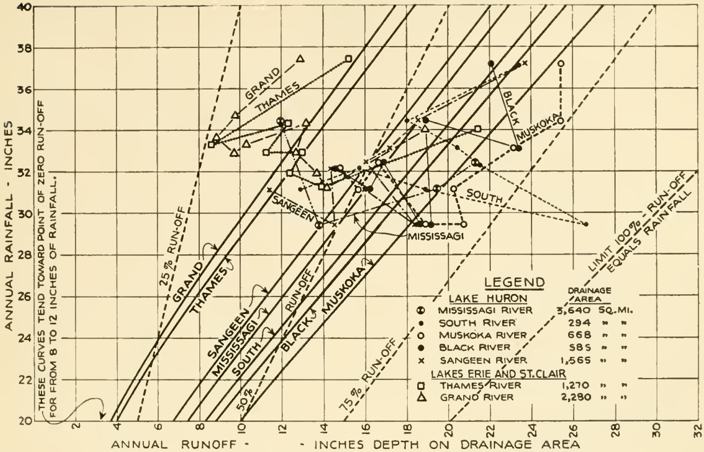
This is not strange when one considers that the percentage of run-off from any particular storm varies greatly with the intensity and total depth of precipitation. As already explained on a previous page (46), when discussing the relation of total annual rainfall to the mean yearly levels of the lakes, this relation is extremely irregular, depending chiefly upon the amount of rain that falls at one time, and the rapidity of the precipitation in inches per hour. A small rainfall of one-quarter inch or less, ordinarily is promptly dissipated in evaporation from the leaves or from the surface of the ground, so that very little of it drains off from surface, or descends thru the ground into the underflow.

On the other hand, when rain falls on ground and foliage, the surface of which is already saturated, a large portion flows off into the stream.

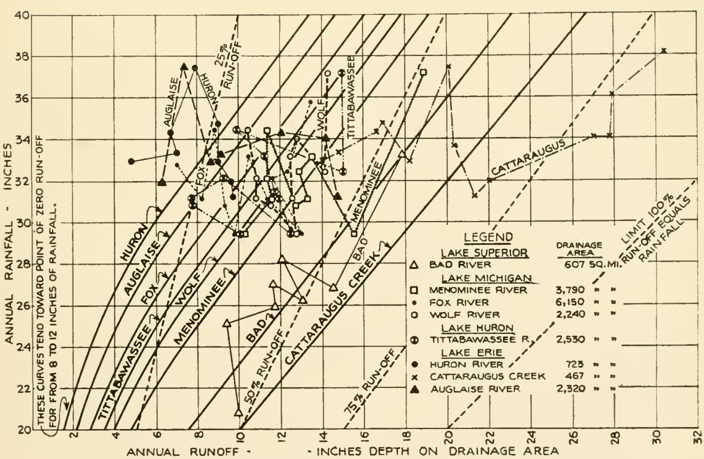
The following diagrams show this variability and serve chiefly as a convenient means of comparing the annual depth of run-off from the different principal streams flowing into each lake.

The diagonal curves drawn for each stream on the following diagrams of relation to run-off are sketched in from general principles. These data shown by the plotted points cover an insufficient range for determining the direction of these lines.

It may require 20 more years of gagings to give a decisive position to these lines of observed relation of run-off to rainfall in the diagrams on the following page.



RELATION RUN-OFF TO RAINFALL - CANADIAN STREAMS
ENTERING LAKES HURON AND ERIE.



RELATION RUN-OFF TO RAINFALL- UNITED STATES STREAMS
ENTERING LAKES SUPERIOR, MICHIGAN, HURON AND ERIE.

NAME OF STREAM	DRAINAGE AREA SQ. MI.	RUN-OFF*——								
		1897–98	1898–99	1899–1900	1900–01	1901–02	1902–03	1903–04	1904–05	1905–06
I. Tributary to Lake Superior										
Bad River near Odanah, Wis.	607	....	....	....	....	....	....	....	....	....
Perch River near Sidnaw, Mich.	60	....	....	....	....	....	....	....	....	....
Poplar River at Lutsen, Minn.	144	....	....	....	....	....	....	....	....	....
Sturgeon River near Sidnaw, Mich.	155	....	....	....	....	....	....	....	....	....
St. Louis River near Thomson, Minn.	3,420	....	....	....	....	....	....	....	....	....
Montreal River at Ironwood, Mich.	73	....	....	....	....	....	....	....	....	....
Whiteface River below Meadowlands, Minn.	446	....	....	....	....	....	....	....	....	....
West Branch of Montreal at Gile, Wis.	70	....	....	....	....	....	....	....	....	....
Cloquet River at Independence, Minn.	698	....	....	....	....	....	....	....	....	....
Aminicon River near Aminicon Falls, Wis.	102	....	....	....	....	....	....	....	....	....
Brule River near Brule, Wis.	162	....	....	....	....	....	....	....	....	....
Beaver Bay River at Beaver Bay, Minn.	120	....	....	....	....	....	....	....	....	....
II. Tributary to Lake Michigan										
Escanaba River near Escanaba, Mich.	800	....	....	....	....	....	....	‡	‡	‡
Menominee River at Twin Falls, Mich.	1,790	....	....	....	....	....	....	....	....	....
Menominee River near Iron Mountain, Mich.	2,420	....	....	....	....	....	‡	‡	‡	18.86
Menominee River below Koss, Mich.	3,790	....	....	....	....	....	....	....	....	....
Brule, (Menominee) River near Florence, Wis.	344	....	....	....	....	....	....	....	....	....
Pine River near Florence, Wis.	488	....	....	....	....	....	....	....	....	....
Pike River at Amberg, Wis.	240	....	....	....	....	....	....	....	....	....
Peshtigo River at High Falls, Wis.	520	....	....	....	....	....	....	....	....	....
Oconto River near Gillett, Wis.	678	....	....	....	....	....	....	....	....	....
Fox River at Berlin, Wis.	1,430	....	7.44	6.68	8.98	7.47	10.19	11.45	14.81	13.10
(a) Fox River at Rapide Croche Dam, Wis.	6,150	6.94	7.73	6.08	10.33	8.09	9.37	10.22	12.12	10.76
St. Joseph River near Buchanan, Mich.	3,940	....	....	....	....	....	....	....	....	10.53
Wolf River at Keshena, Wis.	840	....	....	....	....	....	....	....	....	....
Wolf River at New London, Wis.	2,240	....	....	....	....	....	....	....	....	....
West Branch, Wolf River at Neopit, Wis.	108	....	....	....	....	....	....	....	....	....
Kalamazoo River near Allegan, Mich.	1,470	....	....	....	....	7.33	12.55	14.90	11.95	11.37
Embarrass River near Embarrass, Wis.	395	....	....	....	....	....	....	....	....	....
Little Wolf River at Royalton, Wis.	485	....	....	....	....	....	....	....	....	....
Waupaca River near Waupaca, Wis.	305	....	....	....	....	....	....	....	....	....
Sheboygan River near Sheboygan, Wis.	403	....	....	....	....	....	....	....	....	....
(b) Grand River at North Lansing, Mich.	1,230	x	x	x	x	10.92	14.40	9.32	9.85	‡
Grand River at Grand Rapids, Mich.	4,900	....	....	....	....	10.65	‡	‡	‡	‡
Muskegan River at Newaygo, Mich.	2,350	....	....	....	....	....	‡	‡	7.31	7.64
Milwaukee River at Milwaukee, Wis.	661	....	....	....	....	....	....	....	....	....
Manistee River near Sherman, Mich.	900	....	....	....	....	....	‡	18.56	16.22	16.89
Little Calumet River at Harvey, Ill.	570	....	....	....	....	....	....	....	....	....
III. Tributary to Lake Huron										
Thunder Bay River near Alpend	1,260	....	....	....	....	7.86	28.84	14.77	8.17	12.59
Tittabawassee River at Freeland, Mich.	2,530	....	....	....	....	....	....	‡	‡	‡
An Sable River near Lovells, Mich.	1,000	....	....	....	....	....	....	....	....	....
An Sable River at Bamfield, Mich.	1,420	....	....	....	....	....	‡	‡	‡	13.51

(a) Runoff 1896–97=7.56 inches.
(b) Gage heights only for 1865–96 and 1896–97.
*Values of run-off are for climatic year October 1st to September 30th.

INCHES DEPTH ON WATER-SHED AREA

1906–07	1907–08	1908–09	1909–10	1910–11	1911–12	1912–13	1913–14	1914–15	1915–16	1916–17	1917–18	1918–19	1919–20	1920–21	1921–22	1922–23	1923–24	Average
....	....	....	....	....	....	....	‡	12.05	17.83	9.94	11.62	13.08	14.50	11.71	9.39	....	....	12.51
....	....	....	....	....	....	16.56	17.22	16.02	....	....	....	....	....	....	....	....	....	16.60
....	....	....	....	....	....	‡	12.02	7.36	14.17	8.88	....	....	....	....	....	....	....	10.61
....	....	....	....	....	....	18.69	19.65	17.85	....	....	....	....	....	....	....	....	....	18.73
....	....	....	6.50	7.77	7.60	9.07	‡	‡	....	....	....	....	....	....	....	....	....	7.74
....	....	....	....	....	....	....	....	....	....	....	‡	10.92	13.24	10.20	‡	....	....	11.45
....	....	....	‡	‡	‡	‡	‡	‡	‡	‡	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....	....	‡	14.88	16.08	13.35	13.51	10.29	11.80	13.32
....	....	....	13.27	9.24	8.54	9.40	‡	‡	16.59	9.17	....	....	....	....	....	....	....	11.03
....	....	....	....	....	....	....	....	12.29	‡	....	....	....	....	....	....	....	....	12.29
....	....	....	....	....	....	....	‡	17.79	22.33	‡	....	....	....	....	....	....	....	20.06
....	....	....	....	....	14.16	14.06	20.28	....	....	....	....	....	....	....	....	....	....	16.17
‡	‡	‡	12.00	15.68	22 49	x	x	x	....	....	....	....	....	....	....	....	....	16.72
....	....	....	....	....	....	....	....	12.90	23.36	16.77	11.66	12.96	13.31	12.09	13.39	....	....	14.55
‡	12.42	‡	11 08	11.63	17.91	14.76	‡	....	....	....	....	....	....	....	....	....	....	14.44
‡	12.17	....	....	....	....	‡	12.73	11.56	18.88	15.49	11.34	13.45	13.32	11.38	12.86	10.02	9.07	12.69
....	....	....	....	....	....	....	....	14.62	‡	....	....	....	....	....	....	....	....	14.62
....	....	....	....	....	....	....	‡	‡	17.49	15.49	11.82	12.92	14.70	13.19	12.90	10.98	10.77	13.36
....	....	....	....	....	....	....	‡	13.48	19.53	17.33	13.15	14.71	15.39	14.31	15.42	12.34	12.98	14.86
....	....	....	....	....	‡	14.37	13.44	11.25	16.46	16.33	13.16	14.01	13.78	13.78	14.66	11.60	13.03	13.81
....	9.46	‡	‡	‡	‡	‡	‡	13.55	16.75	15.55	12.68	15.10	13.78	12.72	17.54	12.42	12.72	13.84
11.96	11.03	8.96	7.78	7.97	13.84	12.83	8.69	10.37	14.44	14.63	13.06	10.32	11.69	9.41	14.33	....	....	10.89
11.61	9.49	8.07	6.63	7.00	13.43	11.83	9.26	8.19	14.27	12.90	11.53	10.46	11.45	8.82	12.30	9.84	12.06	9.94
....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	10.53
‡	12.84	‡	‡	‡	18.42	17.13	13.52	12.50	16.03	14.20	12.14	14.47	13.70	12.64	14.53	....	....	14.34
....	....	....	....	....	....	....	11.51	10.82	14.31	12.82	10.85	12.48	12.57	10.42	14.14	11.09	12.50	12.14
....	....	....	....	....	‡	‡	14.63	12.66	15.38	‡	....	....	....	....	....	....	....	14.22
11.29	‡	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	11.56
....	....	....	....	....	....	....	....	....	....	....	....	....	11.71	10.59	14.29	9.72	12.26	11.71
....	....	....	....	....	....	....	....	10.08	15.44	13.48	12.72	14.81	14.57	11.63	15.40	12.22	14.91	13.52
....	....	....	....	....	....	....	....	....	....	11.71	11.29	12.14	12.34	10.45	12.54	11.14	12.32	11.74
....	....	....	....	....	....	....	....	....	....	9.60	10.87	6.08	8.94	6.78	9.23	7.26	....	8.35
....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	11.12
x	x	x	x	x	x	x	x	x	x	x	x	....	....	....	....	....	....	10.65
....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	7.48
....	....	....	....	....	....	....	....	10.89	11.57	11.62	10.43	6.71	8.41	7.27	9.92	7.80	12.84	9.75
16.75	16.33	16.16	15.06	17.31	19.01	18.80	17.28	15.77	‡	....	....	....	....	....	....	....	....	17.01
....	....	....	....	....	....	....	....	....	....	5.37	6.79	10.32	8.65	5.43	9.94	6.59	13.65	8.59
11.33	10.51	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	14.01
‡	‡	x	x	x	‡	11.81	7.78	11.88	14.95	10.01	9.22	11.25	7.73	9.90	14.97	12.62	7.84	10.82
....	....	11.88	10.70	12.04	16.43	14.08	11.28	....	....	....	....	....	....	....	....	....	....	12.73
15 44	11.90	8.65	12.21	13.19	17.23	14.77	....	....	....	....	....	....	....	....	....	....	....	13.86

NAME OF STREAM	DRAINAGE AREA SQ. MI.	RUN-OFF*——								
		1897–98	1898–99	1899–1900	1900–01	1901–02	1902–03	1903–04	1904–05	1905–06
IV. Tributary to Lake Erie										
Huron River at Barton, Mich.	723	....	....	....	....	....	....	....	....	....
Huron River at Flat Rock, Mich.	1,000	....	....	....	....	....	....	....	11.33	11.98
Cattaraugus Creek at Versailles, N. Y.	467	....	....	....	....	....	....	....	....	....
Hudson River at Geddes, Mich.	757	....	....	....	....	....	....	‡	‡	‡
Maumee River at Antwerp, Ohio	2,130	....	....	....	....	....	....	....	....	....
Maumee River at Waterville, Ohio	6,310	....	....	....	....	....	....	....	....	....
Tiffin River near Stryker, Ohio	383	....	....	....	....	....	....	....	....	....
Auglaize River near Defiance, Ohio	2,320	....	....	....	....	....	....	....	....	....
Blanchard River at Glandorf, Ohio	643	....	....	....	....	....	....	....	....	....
Sandusky River near Upper Sandusky, Ohio	299	....	....	....	....	....	....	....	....	....
Cuyahoga River at Old Portage, Ohio	405	....	....	....	....	....	....	....	....	....
Cuyahoga River at Independence, Ohio	709	....	....	....	....	....	....	....	....	....
Conneaut Creek at Amboy, Ohio	178	....	....	....	....	....	....	....	....	....
V. Tributary to Lake Ontario										
Little Tonawanda Creek at Linden, N. Y.	22	....	....	....	....	....	....	....	....	....
Genesee River at Scio, N. Y.	288	....	....	....	....	....	....	....	....	....
Genesee River at St. Helena, N. Y.	992	....	....	....	....	....	....	....	....	....
Genesee River at Mt. Morris	1,070	....	....	....	....	....	....	‡	‡	13.13
Genesee River at Jones Bridge, near Mt. Morris, N. Y.	1,400	....	....	....	....	....	....	‡	‡	‡
Genesee River at Driving Park Ave., Rochester, N. Y.	2,460	....	....	....	....	....	....	....	‡	‡
Canaseraga Creek near Dansville, N. Y.	158	....	....	....	....	....	....	....	....	....
Canaseraga Creek at Shakers Crossing, N. Y.	335	....	....	....	....	....	....	Current Meter		
Seneca River at Baldwinsville, N. Y.	3,100	....	‡	9.73	14.48	14.36	16.37	18.84	14.55	14.28
(c) Skaneateles Lake Outlet at Willow Glen, N. Y.	74.2	13.84	14.18	8.80	17.42	20.44	19.03	20.84	14.42	‡
Keshequa Creek at Craig Colony, Sonyea, N. Y.	70	....	....	....	....	....	....	....	....	....
Conesus Creek near Lâkeville, N. Y.	71	....	....	....	....	....	....	....	....	....
Chittenango Creek at Chittenango, N. Y.	79	....	....	....	....	44.66	39.76	‡	21.73	‡
Candace Lake Outlet near Hemlock, N.Y.	12.6	....	(1.0 sq. mi. lake surface)				....	17.07	12.85	10.44
Owasco Lake Outlet near Auburn, N. Y.	206	....	....	....	....	....	....	....	....	....
Oneida River at Caughdenoy, N. Y.	1,377	....	....	....	....	....	36.70	34.80	29.40	30.12
Orwell Brook near Altmar, N. Y.	22.1	....	....	....	....	....	....	....	....	....
Black River near Boonville, N. Y.	303	....	....	....	....	....	....	....	....	....
Salmon River at Stillwater Bridge near Redfield, N. Y.	191	....	....	....	....	....	....	....	....	....
Salmon River near Prelaski, N. Y.	260	....	....	....	‡	‡	‡	‡	‡	44.72
Black River near Felts Mill, N. Y.	1,851	....	....	....	....	....	22.53	24.46	26.51	26.10
Black River at Watertown, N. Y.	1,890	....	at Black River 1870			....	....	....	....	....
Forestport Feeder near Boonville, N. Y.	....	....	....	....	....	....	....	....	....	....
Black River Canal (flowing south) near Boonville, N. Y.	....	....	....	....	....	....	....	....	....	....
Moose River at McKeever, N. Y.	366	....	....	....	....	....	....	....	....	....
Moose River at Moose River, N. Y.	370	....	....	....	‡	‡	‡	‡	‡	‡
Middle Branch of Moose River at Old Forge, N. Y.	51.5	....	....	....	....	....	....	....	....	....
Beaver River at State Dam near Beaver River, N. Y.	176	....	....	....	....	....	....	....	....	....
Beaver River at Eagle Falls, near Number Four, N. Y.	230	....	....	....	....	....	....	....	....	....
Oswego River at High Dam	5,000	12.52	9.09	9.60	15.73	....	....	....	....	....

(c) Runoff 1895–96 = 16.01 inches; 1896–97 = 13.09 inches.

*Values of run-off are for climatic year, October 1st to September 30th.

INCHES DEPTH ON WATER-SHED AREA—Continued

1906–07	1907–08	1908–09	1909–10	1910–11	1911–12	1912–13	1913–14	1914–15	1915–16	1916–17	1917–18	1918–19	1919–20	1920–21	1921–22	1922–23	1923–24	AVERAGE
....	....	....	....	....	....	....	‡	8.98	12.78	7.90	9.56	8.96	6.97	6.71	9.71	4.80	6.46	8.28
10.04	12.14	7.78	8.07	5.32	x	x	x	x	x	x	x	x	x	x	x	....	....	9.52
....	....	....	....	27.87	27.05	30.40	20.37	16.89	27.75	20.08	21.98	18.20	14.82	16.62	21.38	14.05	....	21.34
8.40	10.63	7.19	7.00	4.66	8.77	13.52	8.66	....	....	....	....	....	....	....	....	....	....	8.63
....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	13.95	....	....	13.95
....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	13.90°	7.78	12.86	11.51
....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	11.76	....	....	11.76
....	....	....	....	....	....	....	....	....	14.22	7.37	6.32	8.60	9.12	12.05	14.75	....	....	10.35
....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	19.73	10.23	15.56	15.17
....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	15.71	....	....	15.71
....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	14.90*	....	....	14.90
....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	‡	15.68	20.90	18.38
....	....	....	....	....	....	18.68	14.94	10.95	23.86	17.33	16.15	18.23	....	14.35	12.43	13.20	15.63	15.98
....	....	....	....	....	....	....	....	....	....	18.95	24.17	20.58	15.12	12.91	18.90	....	....	18.44
....	‡	14.03	15.42	15.71	17.70	19.07	16.30	15.16	26.94	17.18	16.90	17.00	12.62	12.44	17.12	....	....	16.97
18.35	21.01	‡	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	17.50
‡	‡	13.86	14.15	14.41	16.12	17.65	‡	‡	25.49	15.43	17.74	15.83	11.67	11.95	16.38	...	....	15.90
15.63	20.00	12.54	12.53	13.20	14.74	16.22	14.84	11.26	22.17	12.60	15.02	....	....	12.16†	13.96†	11.70†	15.42†	14.63
....	....	....	....	x	‡	‡	‡	‡	‡	‡	‡	....	....	9.38	14.10	....	....	11.74
Measurements Only—									x	x	x	x	x	x	x	....	....	....
15.27	15.33	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	14.80
11.26	18.11	....	....	....	....	....	....	....	....	....	‡	12.75	11.97	....	....	....	....	15.21
....	....	....	....	x	‡	....	....	....	‡	‡	‡	8.36	6.86	7.57	10.11	....	....	8.22
....	....	....	....	....	....	....	....	....	....	....	....	....	‡	8.06	8.95	....	....	8.50
....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	35.38
16.46	16.88	9.50	8.82	5.48	12.40	16.90	....	....	....	....	....	‡	‡	‡	‡	....	....	12.68
....	....	....	....	....	....	‡	21.03	17.86	25.98	19.19	18.75	17.54	15.46	15.45	24.32	....	....	19.51
23.00	29.53	28.10	23.14	18.40	24.51	‡	....	....	....	....	....	....	....	....	....	....	....	27.77
....	....	....	....	‡	‡	36.72	‡	‡	‡	....	....	....	....	....	....	....	....	36.72
....	....	....	....	‡	34.77	33.20	23.41	15.80	30.95	35.52	29.68	28.31	27.82	30.22	34.89	24.55	27.31	28.95
....	....	....	....	‡	49.15	53.16	....	....	....	....	....	....	....	....	....	....	....	51.83
‡	‡	‡	x	‡	47.76	49.08	‡	....	....	....	....	....	....	....	....	....	....	47.19
‡	‡	25.64	21.45	22.48	31.35	....	....	....	....	....	....	....	....	....	....	....	....	25.06
....	....	....	....	....	....	....	....	....	....	....	28.16	26.85	25.75	27.23	31.20	21.23	28.96	27.05
....	....	....	....	....	....	....	....	....	‡	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	—— Discharge Measurements ——							....	....	....
....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	‡	....	....	....
25.85	42.41	32.22	33.53	29.28	33.67	33.71	‡	23.67	31.06	31.46	29.46	31.60	29.74	29.51	36.90	23.84	30.79	31.10
....	....	....	....	....	‡	28.27	24.90	22.76	29.98	30.02	31.31	29.72	24.49	28.18	32.87	....	....	28.25
....	....	28.40	24.03	26.14	25.25	31.00	24.37	21.04	30.73	26.36	29.25	29.23	25.04	27.40	29.67	21.39	28.65	26.74
....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	33.34	....	....	33.34
....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	11.73

°Includes River and Miami and Erie Canal.
xNo discharge measurements, gage heights only, due lack of current meter measurements to determine rating curve.
*Include river and Ohio canal.
†These figures do not represent the natural flow from drainage area on account of inflow and diversion at the crossing of the Barge Canal during navigation season.
‡Incomplete gagings.

RUN-OFF FROM CANADIAN STREAMS* — INCHES DEPTH ON WATER-SHED AREA

NAME OF STREAM	DRAINAGE AREA SQ. MI.	1913–14	1914–15	1915–16	1916–17	1917–18	1918–19	1919–20	1920–21	1921–22	1922–23	1923–24	1924–25
I. Tributary to Lake Superior													
Dog River near Dona, Ont.	1,470	....	....	....	....	....	....	....	....	8.66	7.74	....	....
Matawin River, Glenwater, Ont.	1,025	....	....	....	....	....	....	....	....	....	x	4.71	7.64
Matawin River, near Kaministikwia, Ont.	1,100	....	....	....	....	....	....	....	....	8.27	5.54	....	....
Kaministikwia River near Dona, Ont.	1,470	....	....	....	....	....	....	....	....	....	....	5.26	4.26
Nipigon R., Cameron Falls, Ont.	9,125	....	....	....	....	....	....	....	....	10.86	8.65	7.99	8.80
Magpie River at Steep Hill Falls	635	....	....	....	....	....	....	....	9.35	11.88	5.76	10.58	13.52
Michipicoten R. at High Falls	2,008	....	....	....	....	....	....	x	9.67	x	x	12.58	14.31
Montreal R. at Hudson Bay R. R. Bridge	965	....	....	....	....	....	....	x	x	x	x	....	....
II. Tributary to Lake Huron													
Mississagi R. at Mississagi Bridge	3,640	....	....	....	....	....	....	19.45	11.94	21.30	13.78	10.41	10.22
Spanish River at High Falls	2,558	....	....	....	....	....	....	....	8.29	19.06	11.95	8.95	8.25
Aux Sable River at Massey	524	....	x	23.30	27.90	x	20.54	x	13.10	20.70	15.14	11.74	11.78
Vermilion R. at Aho's Farm	1,680	....	....	....	....	....	....	15.59	10.29	15.35	11.61	10.99	9.73
Wanapitei River near Coniston	1,030	....	....	....	....	....	....	....	....	....	15.66	13.66	13.85
III. Tributary to Lake Nispissing													
Sturgeon R. at Sturgeon Falls	2,655	....	....	....	....	....	....	....	....	18.80	14.00	12.60	13.47
South River at Cox's Chute	166	....	....	....	....	....	....	17.74	18.87	18.71	18.05	18.63	18.65
South R. near Powassan	294	x	12.88	23.44	26.60	15.74	20.40	18.92	18.00	21.25	18.87	16.64	17.38
IV. Tributary to Georgian Bay													
Maganatawan R. (N.Br.) near Burk's Falls	107	....	x	32.20	31.80	19.13	30.29	25.20	25.71	24.95	22.29	22.75	20.65
Maganatawan R. (S.Br.) near Burk's Falls	257	....	x	27.40	27.75	17.05	22.50	18.85	22.16	21.20	17.04	16.98	15.81
Muskoka R. ((N.Br.) near Port Sydney	560	....	x	22.65	23.98	14.06	22.56	20.85	20.49	17.09	17.43	18.57	15.80
Muskoka R. (S.Br.) at Blacks Bridge	668	x	15.65	25.40	20.76	14.74	23.15	20.24	25.40	16.66	18.92	19.90	15.13
Black River near Washago	585	....	x	22.05	19.07	14.55	23.31	16.10	18.98	16.90	18.83	18.87	15.54
Black River near Kimberley	100	....	x	19.40	18.31	15.20	17.64	15.60	21.95	16.55	x	16.54	16.84
Sydenham R. near Owen Sound	71	....	x	19.28	20.80	17.74	16.40	21.00	21.75	18.89	14.69	17.57	14.54
V. Tributary to East Shore of Huron													
Rocky Saugeen River near Markdale	42	....	....	....	....	....	....	x	16.14	12.26	9.83	....	....
Rocky Saugeen River near Traverston	96	....	x	20.20	18.55	15.54	17.38	16.95	19.65	14.84	13.19	16.79	13.94
Saugeen River near Walkerton	850	x	10.80	20.85	17.62	13.35	16.90	15.97	18.05	14.13	14.68	15.83	11.50
Saugeen River near Port Elgin	1,565	x	11.41	23.65	18.40	14.37	17.15	16.05	18.55	16.05	14.51	16.01	11.80
VI. Tributary to Lake St. Clair													
Thames R. (N.Br.) near Fanshawe	585	....	x	20.90	11.40	7.28	11.98	6.68	11.95	14.02	11.67	14.83	6.41
Thames R. (S.Br.) near Ealing	515	....	x	20.25	14.30	10.88	11.67	8.48	12.17	14.62	9.86	15.66	9.43
Thames R. (Main Stream) at Byron	1,230	....	....	....	....	....	....	....	....	....	11.25	15.18	x
Thames R. (Main Stream) at Kilworth	1,270	....	x	21.42	15.20	12.36	12.93	8.60	12.28	13.95	....	....	....
VII. Tributary to Lake Erie													
Grand River at Belwood	280	x	5.53	19.28	13.28	11.25	15.06	10.65	14.54	14.68	12.49	....	....
Grand River near Conestogo	550	6.12	11.36	18.12	11.42	8.09	14.09	9.45	13.45	13.20	11.33	....	....
Speed River at Hespeler	250	x	9.61	18.01	13.35	12.00	13.19	10.20	11.23	13.36	x	....	....
Grand River at Galt	1,360	6.41	8.90	14.87	11.36	10.45	12.16	8.74	11.78	12.68	9.94	11.72	7.50
Nith River near Canning	430	9.94	11.61	x	12.87	x	x	x	13.00	12.96	9.12	....	....
Grand River at York	2,280	8.85	9.76	18.90	12.90	13.68	12.73	10.30	13.16	14.11	9.66	....	....
VIII. Tributary to Lake Ontario													
Credit R. at Cataract Junction	85	....	x	14.36	10.21	15.15	9.89	8.77	8.61	9.57	8.87	8.87	7.44
Moira River near Foxboro	1,038	....	....	x	12.46	11.89	18.83	9.54	11.11	13.33	8.33	12.65	11.36
Napanee R. near Napanee	300	....	....	x	12.25	15.42	23.55	10.54	11.45	13.11	9.29	13.62	13.10

x Gaugings for the year are incomplete.

*For climatic years, October 1st to September 30th

EVAPORATION FROM THE GREAT LAKES

ESTIMATED FROM INFLOW MINUS OUTFLOW FROM EACH GREAT LAKE

Before completing designs for regulating the Great Lakes, it seemed important to study closely the causes of their present irregularities.

It is believed that by tracing the course of the water flow from rainfall to river, and thence through the lakes; and by taking the most careful account that records will permit, of the effect of inflow and outflow upon the levels of the lakes, that a measurement can be had of the loss by evaporation, which although not precise, is at least instructive and will be helpful toward a future intelligent budgetting of the water so as to obtain the maximum of useful water power.

The difference between outflow and inflow (after compensation for rise or fall of lake surface) **can be attributed only to evaporation,** or to lack of precision in measurement of outflow and inflow and of elevation of each lake.

The chief cause of inaccuracy in this estimate of the loss by evaporation, measured by the difference between inflow and outflow, is found in the lack **of information about the extent to which the winter outflow was obstructed by ice.**

Not all of the inflowing streams have been gaged. There seem to have been good gagings summer and winter on a sufficient number to give a fairly accurate measurement of the equivalent inches depth of run-off during the past few years.

The estimates of lake discharge, or outflow, have all been made by formulas established from summer measurement, and the same "average correction for ice" based more on judgment than on direct measurements, has been used in every winter, whether "cold" or "warm", or "average", in its temperatures.

The method of estimating the evaporation, month by month, for each lake, from the hydrographic data was as follows:

The data on inflow, or run-off into the lakes from their tributary streams, summarized in the annual totals of the preceding tables, were worked out in the form of monthly totals of inches depth over the area of the drainage for each important stream, for 10 years back, or as far back as practicable.

Next, these depths of inflow to each lake were converted into equivalent depths on the lake surfaces and combined with the data on total monthly depth of rainfall (and snowfall) on each lake, from about 55 stations around the Great Lakes, described on page 39, which had been used in constructing the rainfall map on page 40.

The average depth of rainfall on each lake was worked out independently for each month.

Next, the monthly discharge from each of the Great Lakes was taken from tables of estimated monthly discharge of the St. Marys, St. Clair and Niagara Rivers, as computed from lake elevation and corrected for rise or fall of lake surface, and diversions, and for ice obstruction by the best data available.

The rise or fall of each lake during each month was found from the tables giving the mean monthly elevation of each, derived from the daily average of height shown by the recording gages.

Wind effects and seiches cause irregularities in these lake heights, which figure large in terms of cubic feet per second of outflow, but whatever is too high from this cause in any month, is balanced by too low a record in the month that follows, so that errors from this source mostly offset one another.

All of these data were combined in tables like the following, with the result shown in the final column, which gives the difference, month by month, between the inflow and the outflow of each lake. The computations were so voluminous that only the final results are printed.

The data on monthly local net water yield for each lake as used in the following tables for computing the difference between inflow and outflow, are the same as those given in the tables on pages 50 and 51, except that the values have been transformed into equivalent inches depth on the respective lake surfaces.

The data on stream-flow from one Great Lake into another, as used in this computation, were those obtained from the U. S. Lake Survey office.

The data on stream flow into the Great Lakes from those tributaries located in the United States were obtained from the U. S. Geological Survey and its Water Supply Papers; while for the Canadian streams the data were obtained from the Dominion Water Power and Reclamation Service of Canada and its Water Resources Papers.

The values for stream gaugings, subsequent to September 1923, are unpublished records and are subject to revision.

Except for errors of observation that mostly balance in the long run, and except for the possibility that the large portion of the drainage areas from which we have no direct gaging, may yield a different depth of run-off from that from the areas whose outflow is gaged, **this difference must be accounted for as evaporation from the lake surfaces.**

It is of interest to follow through these tables month by month and to find such good general agreement in the stream-flow measurements and the relation of run-off to rainfall from year to year. (See pages 68 to 79 inclusive.)

This fact of agreement gives confidence in the accuracy of these stream-flow gagings.

LAKE SUPERIOR—APPROXIMATE EVAPORATION LOSS

Measured inflow from gaugings of local tributaries

Plus rainfall on surface of lake

Minus outflow gauged at Sault Ste. Marie corrected for ice and rise and fall of lake.

Date Year and Month	Estimated Rainfall, Inches Depth on Lake Surface	INFLOW FROM LOCAL TRIBUTARIES — CANADIAN				INFLOW FROM LOCAL TRIBUTARIES — U. S.		Total Weighted Average Inflow from local tributaries, Inches Depth on Lake Surface †	Total Inflow from Local Tributaries plus Rainfall on lake surface, Inches Depth on Lake I+VIII	Local Net Water Yield from Lake. Outflow, Corrected for Rise and Fall of Lake, Minus Inflow from Lake above; Inches Depth on Lake	Computed Evaporation, or Loss between Inflow and Outflow; Inches Depth on Lake Surface. IX—X
		Matawin River near Kaministikwia. Drainage Area = 1,100 Sq. Mi.	Nipigon River at Cameron Falls, Drainage Area = 9,125 Sq. Mi.	Magpie River at Steep Hill Falls, Drainage Area = 635 Sq. Mi.	Michipicoten River at High Falls, Drainage Area = 2,008 Sq. Mi.	Bad River near Odanah, Wis., Drainage Area = 607 Sq. Mi.	West Branch of Montreal River at Gile, Drainage Area = 70 Sq. Mi.				
		Inches Depth on Drainage Area									
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
1921											
January	1.2	....	—	0.45	0.43	0.25	0.43	0.58	1.78	-0.50	2.28
February	1.0	....	—	0.41	0.33	0.25	0.25	1.06	2.06	-1.78	3.84
March	2.4	....	—	0.42	0.46	1.96	1.51	1.45	3.85	0.05	3.80
April	3.0	....	—	1.98	2.13	3.53	5.23	4.07	7.07	3.69	3.38
May	2.4	....	—	1.82	2.34	1.20	1.45	2.88	5.28	5.89	-0.61
June	1.8	....	—	1.34	1.32	0.66	0.80	1.68	3.48	5.10	-1.62
July	4.6	....	—	0.58	0.72	1.38	1.72	1.43	6.03	4.07	1.96
August	2.4	....	—	0.57	0.53	0.31	0.20	0.71	3.11	3.24	-0.13
September	3.5	....	—	0.38	0.38	0.41	0.16	0.58	4.08	1.99	2.09
October	1.6	0.52	1.10	0.40	0.37	0.37	0.30	0.81	2.41	-0.08	2.49
November	1.6	0.38	0.95	0.34	0.34	0.34	0.19	0.69	2.29	-1.77	4.06
December	1.7	0.27	0.89	0.45	—	0.37	0.24	0.67	2.37	-1.28	3.65
Total	**27.2**	—	—	9.14	—	11.03	12.48	**16.61**	**43.81**	**18.62**	**25.19**
1922											
January	1.4	0.20	0.79	0.45	—	0.20	0.19	0.55	1.95	-2.53	4.48
February	2.4	0.17	0.68	0.35	—	0.31	0.19	0.53	2.93	-1.05	3.98
March	1.5	0.21	0.74	0.39	—	0.71	1.08	0.81	2.31	-0.32	2.63
April	2.7	1.37	0.73	1.42	1.19	3.77	6.80	3.27	5.97	4.09	1.88
May	2.4	2.63	0.93	5.63	5.33	1.61	2.81	4.51	6.91	7.31	-0.40
June	3.1	0.81	1.03	1.05	1.80	0.60	0.93	1.63	4.73	4.09	0.64
July	3.4	0.58	1.08	0.68	0.92	0.41	0.33	1.08	4.48	5.14	-0.66
August	1.8	0.66	1.03	0.46	0.69	0.28	0.17	0.91	2.71	3.38	-0.67
September	2.2	0.46	0.92	0.29	0.35	0.42	0.28	0.75	2.95	2.37	0.58
October	1.6	0.20	0.82	0.27	0.30	—	0.16	0.51	2.11	-0.74	2.85
November	3.2	0.26	0.71	0.31	0.35	—	0.46	0.69	3.88	-0.69	4.57
December	2.1	0.25	0.72	0.35	—	—	0.30	0.57	2.67	-1.17	3.84
Total	**27.8**	**7.80**	**10.18**	**11.65**	—	—	**13.70**	**15.80**	**43.60**	**19.88**	**23.72**
1923											
January	2.1	0.20	0.76	0.30	—	—	0.12	0.45	2.55	-1.28	3.83
February	1.4	0.14	0.63	0.19	—	—	0.10	0.34	1.74	-0.40	2.14
March	2.3	0.13	0.63	0.20	—	—	0.10	0.34	2.64	0.05	2.59
April	1.1	0.96	0.59	0.61	—	—	3.39	2.55	3.65	0.85	2.80
May	1.2	0.96	0.67	1.89	2.50	—	1.98	2.64	3.84	4.24	-0.40
June	2.7	0.84	0.68	0.54	0.93	—	1.47	1.56	4.26	2.75	1.51
July	3.8	0.76	0.82	0.38	0.56	—	1.68	1.54	5.34	4.51	0.83
August	2.3	0.28	0.83	0.25	—	—	0.30	0.60	2.90	3.33	-0.43
September	2.8	0.56	0.80	0.47	—	—	0.23	0.73	3.53	2.45	1.08
October	2.8	*0.82	0.79	0.31	1.86	—	0.31	1.30	4.10	1.30	2.80
November	0.9	0.83	0.71	0.24	1.72	—	0.34	1.23	2.13	0.42	1.71
December	1.5	0.67	0.69	0.71	0.96	—	0.18	0.88	2.38	-0.15	2.53
Total	**24.9**	**7.15**	**8.60**	**6.09**	—	—	**10.20**	**14.16**	**39.06**	**18 07**	**20.99**

*Beginning October 1923, the run-off for Kaministikwia River near Dona, Drainage Area 1470 Sq. Mi., is used instead of the run-off from the Matawin River near Kaministikwia.

LAKE SUPERIOR—APPROXIMATE EVAPORATION LOSS
Continued

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
1924											
January	2.2	0.41	0.66	0.50	0.67	—	0.09	0.65	2.85	0.13	2.72
February	1.0	0.33	0.60	0.37	0.51	—	0.07	0.52	1.52	-2.03	3.55
March	0.8	0.29	0.60	0.28	0.54	—	0.09	0.52	1.32	-1.03	2.35
April	1.7	0.24	0.58	0.68	0.67	—	4.25	2.78	4.48	1.25	3.23
May	1.9	0.31	0.65	2.43	1.42	—	3.79	2.81	4.71	3.45	1.26
June	2.2	0.40	0.63	1.57	1.49	—	0.71	1.36	3.56	2.86	0.70
July	3.4	0.35	0.69	0.56	1.07	—	0.39	0.93	4.33	2.73	1.60
August	5.2	0.29	0.68	0.46	0.89	—	1.18	1.25	6.45	4.91	1.54
September	2.9	0.32	0.72	0.46	0.77	—	0.40	0.82	3.72	4.38	-0.66
October	1.3	0.19	0.80	0.37	0.41	—	0.66	0.82	2.12	2.24	-0.12
November	1.8	0.32	0.76	0.55	0.54	—	0.66	0.90	2.70	0.26	2.44
December	1.9	0.47	0.77	0.58	0.60	—	0.38	0.82	2.72	-1.71	4.43
Total	**26.3**	**3.92**	**8.14**	8.81	**9.58**	—	**12.67**	**14.18**	**40.48**	**17.44**	**23.04**
1925											
January	1.1	0.50	0.76	0.38	0.59	—	0.18	0.60	1.70	-2.58	4.28
February	0.9	0.66	0.65	0.30	0.54	—	0.12	0.64	1.54	-0.32	1.86
March	0.7	0.54	0.72	0.32	0.64	—	0.78	1.03	1.73	-0.04	1.77
April	0.9	0.27	0.69	2.42	1.59	—	2.19	2.25	3.15	3.13	0.02
May	1.7	0.29	0.76	3.25	3.00	—	0.50	1.97	3.67	2.93	0.74
June	3.3	0.18	0.77	2.51	2.42	—	0.28	1.56	4.86	5.48	-0.62
July	2.6	0.15	0.75	1.50	1.92	—	0.06	1.13	3.73	4.39	-0.66
August	2.0	0.18	0.70	0.96	1.55	—	0.03	0.93	2.93	3.11	-0.18
September	3.6	0.51	0.67	0.37	0.51	—	0.06	0.57	4.17	0.78	3.39
October	2.0	—	—	—	—	—	—	—	—	—	—
November	1.2	—	—	—	—	—	—	—	—	—	—
December	1.6	—	—	—	—	—	—	—	—	—	—
Total	**21.6**	—	—	—	—	—	—	—	—	—	—

†Note that column VIII in the above table relates to a very different depth from the depth of run-off from the land, for which yearly totals are given on pages 60 to 64 inclusive.

Although both relate to the same quantity of water, that above is spread over the area of the lake while in the previous table it is spread over the area of the land. The depth on the lake is computed from that on the land on the basis of the relation of area of lake surface to that of land surface. For example, since the land area tributary to Lake Superior is 54 per cent greater than the area of the lake, the figures in column VIII are 54 per cent larger than the depth of run-off computed from the land.

Measured inflow from gagings of local tributaries, plus rainfall on
for ice, diversions and rise or fall of

Date Year and Month	Estimated Rainfall, Inches Depth on Lake Surface	INFLOW FROM LOCAL TRIBUTARIES — CANADIAN: Mississagi River at Mississagi Bridge, Drainage Area=3640 Sq. Mi.	Spanish River at High Falls, Drainage Area=2558 Sq. Mi.	Aux Sable River at Massey, Drainage Area=524 Sq. Mi.	Vermillon River at Aho's Farm, Drainage Area=1680 Sq. Mi.	Wanapitei River near Coniston, Drainage Area=1030 Sq. Mi.	Sturgeon River at Sturgeon Falls, Drainage Area=2655 Sq. Mi.	South River near Powassan, Drainage Area=294 Sq. Mi.	Maganatawan River (N. Br.) near Burks Falls, Drainage Area=107 Sq. Mi.	Maganatawan River (S. Br.) near Burks Falls, Drainage Area=257 Sq. Mi.	Muskoka River (N. Br.) near Port Sydney, Drainage Area=560 Sq. Mi.	Muskoka River (S. Br.) at Blacks Bridge, Drainage Area=668 Sq. Mi.	Black River near Washage, Drainage Area=585 Sq. Mi.	Beaver River near Kimberley, Drainage Area=100 Sq. Mi.	Sydenham River near Owen Sound Drainage Area=71 Sq. Mi.	Saugeen River near Port Elgin, Drainage Area=1565 Sq. Mi.
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI
1915																
Jan.	1.90	....	....	—	....	....	....	0.51	....	....	....	1.16	....	....	....	0.87
Feb.	2.31	....	....	—	....	....	....	0.51	....	....	....	0.95	....	....	....	1.92
Mar.	0.75	....	....	—	....	....	....	0.67	....	....	....	1.02	....	....	....	1.97
April	1.04	....	....	—	....	....	....	3.87	....	....	....	2.93	....	....	....	1.85
May	2.99	....	....	—	....	....	....	1.53	....	....	....	2.16	....	2.01	....	0.60
June	3.44	....	....	—	....	....	....	1.03	....	....	....	2.05	1.03	0.32	....	0.43
July	3.10	....	....	1.18	....	....	....	0.67	....	....	0.76	1.15	0.35	0.69	0.37	0.38
Aug.	3.85	....	....	0.48	....	....	....	1.00	0.91	0.92	0.60	1.01	0.29	0.50	0.45	0.54
Sept.	4.32	....	....	0.61	....	....	....	0.61	0.33	0.80	0.50	0.86	0.30	0.58	0.47	0.81
Oct.	1.64	....	....	1.25	....	....	....	1.34	1.70	1.39	1.69	1.06	0.98	0.66	0.67	0.96
Nov.	3.02	....	....	1.50	....	....	....	1.11	1.73	1.32	1.27	0.96	0.77	0.78	0.97	1.00
Dec.	1.70	....	....	1.33	....	....	....	0.97	2.02	1.55	1.40	1.07	0.99	0.83	0.94	1.40
Total	**30.06**	....	....	—	....	....	....	**13.82**	—	—	—	**16.38**	—	—	—	**12.73**
1916																
Jan.	3.30	....	....	0.80	....	....	....	1.50	2.03	1.69	1.64	1.34	1.65	2.95	3.55	3.75
Feb.	1.39	....	....	0.79	....	....	....	1.19	2.74	2.25	2.05	2.19	2.56	2.74	1.46	2.80
Mar.	2.52	....	....	0.79	....	....	....	1.63	1.58	1.51	1.18	1.88	1.84	2.35	2.01	3.10
April	2.52	....	....	5.22	....	....	....	8.28	8.95	5.96	6.38	5.19	7.40	3.68	3.99	5.49
May	3.76	....	....	4.02	....	....	....	3.86	5.50	5.22	3.60	5.13	3.63	2.18	2.17	2.00
June	4.94	....	....	4.62	....	....	....	1.65	3.60	3.25	1.99	3.58	1.41	1.44	2.10	1.41
July	1.36	....	....	2.15	....	....	....	0.63	1.02	1.62	0.67	1.41	0.49	0.66	0.63	0.50
Aug.	2.57	....	....	0.36	....	....	....	0.35	0.32	0.66	0.40	0.73	0.18	0.51	0.37	0.33
Sept.	3.92	....	....	0.43	....	....	....	0.87	0.73	0.74	0.27	0.64	0.09	0.43	0.30	0.29
Oct.	3.99	....	....	1.62	....	....	....	1.99	2.40	1.39	1.04	0.69	0.56	0.58	0.44	0.44
Nov.	2.52	....	....	2.71	....	....	....	2.14	2.94	2.90	1.78	0.86	1.36	0.98	0.61	0.65
Dec.	2.77	....	....	3.15	....	....	....	3.48	4.28	3.24	3.66	2.19	3.05	1.78	1.90	1.40
Total	**35.56**	....	....	**26.66**	....	....	....	**27.57**	**36.09**	**30.43**	**24.66**	**25.83**	**24.22**	**20.28**	**19.53**	**22.16**
1917																
Jan.	1.84	....	....	0.93	....	....	....	0.78	1.08	1.57	1.22	1.81	0.94	1.25	0.76	0.88
Feb.	1.28	....	....	0.33	....	....	....	0.39	0.88	1.13	0.37	0.92	0.44	1.18	0.59	0.39
Mar.	2.25	....	....	0.49	....	....	....	1.30	1.10	1.19	0.71	0.75	1.71	1.86	3.87	3.66
April	2.72	....	....	2.91	....	....	....	5.57	7.80	4.96	6.42	3.87	5.65	3.23	4.86	3.80
May	2.58	....	....	4.47	....	....	....	3.65	3.95	4.06	3.15	3.45	2.57	2.18	1.74	1.70
June	4.72	....	....	5.18	....	....	....	2.15	2.19	2.14	1.79	2.61	1.19	1.45	1.48	1.36
July	2.64	....	....	4.79	....	....	....	2.42	3.90	2.68	2.64	2.10	0.96	1.82	3.57	3.03
Aug.	1.85	....	....	0.85	....	....	....	1.24	0.87	1.51	0.71	0.88	0.50	1.03	0.62	0.69
Sept.	1.93	....	....	0.47	....	....	....	0.53	0.44	0.88	0.37	0.58	0.18	0.91	0.39	0.40
Oct.	3.65	....	....	0.54	....	....	....	1.53	1.41	0.49	0.58	0.53	0.89	1.07	0.67	0.68
Nov.	1.16	....	....	0.57	....	....	....	1.39	1.53	0.79	0.95	0.66	0.86	0.98	0.74	0.63
Dec.	1.74	....	....	0.48	....	....	....	0.82	0.81	0.80	0.96	1.32	0.58	1.03	0.83	0.76
Total	**28.36**	....	....	**22.01**	....	....	....	**21.77**	**25.96**	**22.20**	**19.87**	**19.48**	**16.47**	**17.99**	**20.12**	**17.98**

.... Indicates no gaging.
— Indicates record not available.
( ) Indicates interpolated value.

APPROXIMATE EVAPORATION LOSS

surface of lake, minus outflow gaged in St. Clair River corrected lake, minus inflow from Lake Superior.

INFLOW FROM LOCAL TRIBUTARIES — UNITED STATES																
Menominee River below Koss, Drainage Area=3790 Sq. Mi.	Pine River near Florence Drainage Area=488 Sq. Mi.	Pike River at Amberg, Drainage Area=240 Sq. Mi.	Peshtigo River at High Falls, Drainage Area=520 Sq. Mi.	Oconto River near Gillett, Drainage Area=678 Sq. Mi.	Fox River at Rapide Croche Dam, Drainage Area=6150 Sq. Mi.	Wolf River at New London, Drainage Area=2240 Sq. Mi.	Little Wolf River at Royalton, Drainage Area=485 Sq. Mi.	Waupaca River near Waupaca, Drainage Area=305 Sq. Mi.	Sheboygan River near Sheboygan, Drainage Area=403 Sq. Mi.	Milwaukee River near Milwaukee, Drainage Area=661 Sq. Mi.	Little Calumet River at Harvey, Drainage Area=570 Sq. Mi.	Tittabawassee River at Freeland, Drainage Area=2530 Sq. Mi.	Total Weighted Average Inflow from local tributaries, Inches Depth on Lake Surface	Total Inflow from Local Tributaries Plus Rainfall on lake surface, Inches Depth on Lake. I+XXX	Local Net Water Yield from Lake. Outflow Corrected for Rise and Fall of Lake, Minus Inflow from Lake Above; Inches Depth on Lake	Computed Evaporation, or Loss between Inflow and Outflow; Inches Depth on Lake Surface. XXXI—XXXII
XVII	XVIII	XIX	XX	XXI	XXII	XXIII	XXIV	XXV	XXVI	XXVII	XXVIII	XXIX	XXX	XXXI	XXXII	XXXIII
0.48	0.44	0.65	0.60	0.60	0.59	0.42	0.60	....	....	.28	....	0.56	1.38	3.28	0.14	3.14
0.47	0.40	0.65	0.50	0.61	0.71	0.59	0.82	....	....	2.00	....	1.27	2.15	4.46	4.64	−0.18
0.59	0.61	0.75	0.73	0.94	1.38	1.20	1.21	....	....	2.18	....	2.13	2.90	3.65	1.06	2.59
1.76	—	2.28	1 45	2.09	0.97	1.65	1.62	....	....	0.77	....	1.56	3.64	4.68	1.96	2.72
1.98	—	1.89	1.51	1.79	0.66	1.38	1.20	....	....	1.22	....	0.90	2.46	5.45	4.78	0.63
1.36	1.16	1.50	1.06	1.61	0.66	1.16	0.78	....	....	0.87	....	(0.85)	2.03	5.47	4.68	0.79
1.18	0.88	1.21	1.01	0.96	0.58	0.78	0.64	....	....	0.28	....	0.56	1.51	4.61	3.74	0.87
0.94	0.95	1.16	1.10	1.10	0.48	0.76	0.56	....	....	0.33	....	0.84	1.48	5.33	5.46	−0.13
0.76	0.77	0.75	0.90	1.23	0.63	0.88	0.73	....	....	0.96	....	1.37	1.66	5.98	0.30	5.68
1.29	0.89	0.99	0.73	0.88	0.95	0.78	0.60	....	....	0.43	....	0.84	2.15	3.79	0.51	3.28
1.52	1.46	1.63	0.93	1.35	0.88	1.10	1.03	....	....	0.80	....	0.89	2.30	5.32	−1.64	6.96
0.99	1.10	1.34	0.83	0.96	1.00	0.84	0.85	....	....	0.67	....	0.88	2.22	3.92	1.79	2.13
13.32	—	**14.80**	**11.35**	**14.12**	**9.49**	**11.54**	**10.64**	....	....	**10.79**	....	**12.65**	**25.88**	**55.94**	**27.45**	**28.49**
0.66	0.43	0.86	0.53	0.61	0.89	0.56	0.64	....	....	1.51	....	1.11	2.82	6.12	−0.69	6.81
0.55	0.38	0.71	0.39	0.51	0.91	0.45	0.64	....	....	1.05	....	0.98	2.65	4.04	3.20	0.84
0.57	0.59	0.87	0.91	0.88	1.02	0.61	1.56	....	....	1.80	....	1.84	2.73	5.25	3.18	2.07
4.00	3.59	3.32	2.59	3.25	2.39	2.92	3.22	....	....	1.60	....	3.00	8.55	11.07	8.48	2.59
2.63	2.11	1.99	2.50	2.19	2.25	2.01	1.51	....	....	1.34	....	2.02	5.62	9.38	9.30	0.08
3.18	3.42	3.25	3.12	2.87	1.91	2.73	2.92	....	....	1.47	....	1.85	5.05	9.99	9.92	0.07
1.31	1.26	1.71	1.57	1.22	0.93	0.98	0.76	....	....	0.21	....	0.63	2.05	3.41	5.14	−1.23
0.82	0.76	1.18	1.07	0.90	0.61	0.59	0.62	....	....	0.46	....	0.47	1.22	3.79	−0.39	4.18
1.36	1.50	1.68	1.29	1.13	0.53	0.74	1.09	..	....	0.23	....	0.44	1.42	5.34	−2.40	7.94
1.50	1.43	1.89	1.63	1.35	0.72	1.03	1.22	1.06	0.35	0.80	0.26	0.59	1.99	5.98	0.02	5.96
1.65	1.57	1.66	1.62	1.66	1.08	1.47	1.33	1.02	0.96	1.20	0.28	0.75	2.77	5.29	3.99	1.30
0.92	0.72	1.16	1.06	0.96	1.14	0.88	0.77	0.73	0.72	0.41	0.41	0.70	3.14	5.91	1 00	4.91
19.15	**17.76**	**20.28**	**18.28**	**17.53**	**14.38**	**14.97**	**15.28**	—	—	**12.08**	—	**14.38**	**40.01**	**75.57**	**40.75**	**35.52**
0.62	0.43	0.72	0.56	0.61	1.16	0.53	0.41	0.63	0.22	0.20	0.49	0.52	1.84	3.68	0.38	3.30
0.50	0.35	0.62	0.71	0.53	0.81	0.41	0.40	0.55	0.14	0.19	0.25	0.51	1.20	2.48	0.97	1.51
0.66	0.69	1.48	1.09	1.23	0.98	1.04	2.49	1.53	1.99	3.50	0.98	1.48	3.03	5.28	4.29	0.99
2.36	2.15	2.54	1.75	2.60	2.21	2.48	2.20	1.60	1.52	1.35	1.01	1.33	6.23	8.95	7.05	1.90
2.42	2.79	1.81	1.92	1.67	1.42	1.53	1.23	1.07	1.01	1.10	0.47	1.45	4.37	6.95	6.93	0.02
2.12	2.77	2.29	2.56	2.02	1.30	1.42	1.36	1.14	1.66	1.81	0.61	0.92	3.72	8.44	8.47	−0.03
1 00	1.06	1.07	1.21	1.12	0.86	0.79	0.73	0.85	0.51	0.65	0.35	1.03	3.26	5.90	7.51	−1.61
0.89	0.73	1.23	1.22	0.95	0.72	0.65	0.64	0.77	0.28	0.16	0.13	0.33	1.55	3.40	3.06	0.34
0.85	0.80	0.86	1.00	0.85	0.50	0.59	0.70	0.76	0.24	0.25	0.13	0.40	1.14	3.07	1.24	1.83
0.98	1.28	0.98	0.80	0.83	0.51	0.59	0.72	0.37	0.42	0.78	0.24	0.35	1.46	5.11	−0.40	5.51
0.84	0.68	0.89	0.86	0.87	0.64	0.64	0.76	0.74	0.52	0.68	0.26	0.46	1.48	2.64	1.16	1.48
0.50	0.43	0 45	0.79	0.51	0.77	0.41	0.44	0.58	0.13	0.27	0.21	0.57	1.44	3.18	−2.28	5.46
13.74	**14.16**	**14.94**	**14.47**	**13.79**	**11.88**	**11.08**	**12.08**	**10.59**	**8.64**	**10.94**	**5.13**	**9.35**	**30.72**	**59.08**	**38.38**	**20.70**

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI
1918																
Jan.	3.13	....	....	(0.50)	....	....	....	0.49	0.47	0.74	0.47	0.49	0.32	1.00	2.10	0.36
Feb.	2.03	....	....	(0.40)	....	....	....	0.36	0.34	0.47	0.47	0.50	0.24	0.95	1.11	0.79
Mar.	1.40	....	....	(1.35)	....	....	....	1.31	1.46	1.13	1.45	0.71	2.21	1.55	5.72	4.99
April	2.43	....	....	3.12	....	....	....	4.32	6.20	4.76	4.13	2.61	5.44	3.38	3.80	3.14
May	4.25	....	....	3.58	....	....	....	2.72	3.52	3.51	2.81	2.65	2.05	1.48	1.33	1.17
June	1.87	....	....	3.31	....	....	....	1.15	1.42	1.82	0.89	2.45	1.16	0.91	0.61	0.62
July	1.42	....	....	2.80	....	....	....	0.58	0.71	0.86	0.54	1.54	0.45	0.90	0.37	0.38
Aug.	2.15	....	....	0.62	....	....	....	0.39	0.44	0.99	0.44	0.59	0.23	0.95	0.26	0.29
Sept.	2.67	....	....	0.52	....	....	....	0.65	0.80	0.69	0.37	0.70	0.48	0.97	0.30	0.55
Oct.	3.14	....	....	1.29	....	....	....	2.04	3.13	1.88	1.87	1.56	1.15	1.00	0.39	0.56
Nov.	2.92	....	....	2.43	....	....	....	2.10	2.86	2.17	1.83	2.17	1.73	1.07	1.00	1.23
Dec.	2.99	....	....	1.85	....	....	....	1.75	2.81	1.83	2.40	1.91	2.76	1.31	2.19	2.09
Total	**30.40**	....	....	—	....	....	....	**17.86**	**24.16**	**20.85**	**17.67**	**17.88**	**18.22**	**15.47**	**19.18**	**16.17**
1919																
Jan.	1.24	....	....	1.08	....	....	....	1.04	1.71	1.65	1.77	2.04	3.14	1.33	1.04	2.51
Feb.	2.14	....	....	0.97	....	....	....	0.59	0.91	1.18	1.13	1.27	0.86	1.02	1.07	0.95
Mar.	2.67	....	....	1.37	....	....	....	2.56	3.17	1.69	2.42	1.77	4.10	2.58	4.66	4.51
April	3.01	....	....	3.56	....	....	....	4.17	6.69	4.51	5.04	4.07	4.47	2.50	2.32	2.15
May	2.90	....	....	3.23	....	....	....	3.46	5.29	3.59	3.39	3.45	2.85	2.65	1.79	1.85
June	2.33	....	....	2.63	....	....	....	1.40	2.21	2.01	1.18	2.57	1.55	1.36	0.52	0.52
July	2.16	....	....	0.80	....	....	....	0.32	0.44	0.76	0.38	1.33	0.48	0.83	0.32	0.34
Aug.	2.04	....	....	0.50	....	....	....	0.50	0.43	0.68	0.43	0.54	0.18	0.98	0.26	0.26
Sept.	3.44	....	....	1.16	....	....	....	0.47	0.68	0.56	0.74	0.46	0.12	1.00	0.24	0.27
Oct.	4.20	1.28	....	2.47	1.22	1.55	....	1.37	1.36	0.92	2.39	0.92	0.38	1.11	0.41	0.57
Nov.	3.09	2.45	....	2.60	1.65	1.43	....	2.43	3.26	2.15	3.50	2.70	1.93	1.27	1.19	1.19
Dec.	1.48	1.78	....	2.05	1.21	1.50	....	2.14	2.76	2.45	2.95	2.99	0.22	1.46	1.85	1.18
Total	**30.70**	—	....	**22.42**	—	—	....	**20.45**	**28.91**	**22.15**	**25.32**	**24.11**	**20.28**	**18.09**	**15.67**	**16.30**
1920																
Jan.	1.52	0.66	....	0.96	0.71	1.15	....	0.60	0.85	1.04	0.88	1.53	0.48	1.06	1.04	0.53
Feb.	0.80	0.41	....	0.64	0.41	0.82	....	0.44	0.57	0.66	0.46	0.91	0.29	0.92	1.16	0.41
Mar.	3.35	1.41	....	(1.50)	1.33	1.41	....	3.15	3.63	1.41	2.22	1.45	3.25	2.49	8.95	6.27
April	2.72	4.27	....	(3.60)	3.34	1.84	....	3.85	5.84	4.73	4.38	3.15	4.24	1.98	3.30	2.75
May	1.35	3.48	....	2.38	2.42	2.99	....	1.81	3.56	2.65	2.00	2.73	1.97	1.57	1.35	1.04
June	3.89	1.74	....	1.85	1.46	2.34	....	0.75	0.89	0.68	0.81	1.97	1.06	1.04	0.64	0.59
July	2.35	1.07	....	2.44	0.93	2.10	....	1.19	1.21	0.72	0.58	1.35	0.31	1.07	0.55	0.72
Aug.	2.29	0.40	....	0.54	0.73	1.30	....	0.71	0.55	0.91	0.22	0.39	0.05	0.81	0.34	0.44
Sept.	2.45	0.40	....	0.43	0.24	0.78	....	0.57	0.68	0.54	0.46	0.35	0.09	0.71	0.27	0.34
Oct.	1.91	0.35	0.54	0.38	0.18	0.65	....	0.80	0.85	0.77	0.68	0.60	0.25	1.10	0.49	0.62
Nov.	2.33	0.33	0.35	0.49	0.24	0.79	....	1.10	2.15	1.27	1.27	1.12	0.95	1.43	1.66	1.51
Dec.	3.82	0.50	0.38	1.11	0.47	0.68	....	1.05	2.22	1.65	2.51	1.43	2.90	1.68	2.10	2.25
Total	**28.78**	**15.02**	—	**16.32**	**12.46**	**16.85**	....	**16.02**	**23.00**	**17.03**	**16.47**	**16.98**	**15.84**	**15.86**	**21.85**	**17.47**
1921																
Jan.	0.96	0.46	0.51	0.84	0.46	0.47	....	0.86	1.84	1.64	1.85	2.04	1.27	2.30	3.80	2.45
Feb.	1.27	0.36	0.38	0.45	0.36	0.38	....	0.62	0.95	0.96	0.70	1.42	0.44	2.05	1.19	0.94
Mar.	3.95	1.00	0.42	1.43	1.30	0.94	....	5.57	6.68	4.71	5.01	3.80	5.54	5.43	5.72	5.25
April	3.71	3.87	1.74	3.17	3.26	1.25	....	3.47	6.15	5.86	4.90	6.23	4.28	2.42	2.28	2.07
May	1.57	2.40	1.29	1.97	1.80	1.41	....	2.26	2.45	2.49	1.97	3.14	1.73	1.68	1.40	1.21
June	1.51	1.30	0.70	2.07	1.12	1.00	....	0.69	0.96	1.10	0.67	4.93	1.16	1.15	1.55	0.93
July	2.47	0.61	0.60	0.73	0.39	0.91	....	0.55	0.44	0.80	0.35	0.53	0.29	0.92	0.68	0.55
Aug.	4.32	0.40	0.73	0.49	0.34	1.08	....	0.50	0.62	0.45	0.30	0.29	0.13	0.86	0.52	0.42
Sept.	4.14	0.35	0.65	0.42	0.39	0.81	....	0.52	0.30	0.50	0.29	0.31	0.06	0.99	0.47	0.32
Oct.	3.30	1.37	0.84	1.30	0.36	0.59	1.07	0.93	0.70	0.47	0.35	0.40	0.17	1.31	0.63	0.55
Nov.	2.47	1.08	0.87	0.96	0.48	0.73	0.98	1.40	1.85	1.08	0.42	0.37	0.34	0.95	0.82	0.50
Dec.	3.42	1.69	1.49	2.01	1.23	0.95	1.11	1.54	3.23	2.24	2.08	0.63	0.98	1.19	2.32	0.66
Total	**33.09**	**14.89**	**10.22**	**15.84**	**11.49**	**10.52**	—	**18.91**	**26.17**	**22.30**	**18.89**	**24.09**	**16.39**	**21.25**	**21.38**	**15.85**
1922																
Jan.	1.59	0.86	1.16	0.98	0.49	0.65	0.69	0.76	1.38	1.59	1.23	1.04	0.70	0.99	1.02	0.61
Feb.	2.82	0.51	1.07	0.66	0.30	0.61	0.78	0.60	1.04	0.73	0.50	0.96	0.42	1.00	0.89	0.45
Mar.	2.66	0.70	1.29	1.02	0.48	0.71	1.33	2.31	1.99	1.58	1.10	1.05	2.38	2.03	5.50	2.03
April	3.51	5.13	3.85	5.39	5.81	3.15	5.13	8.50	9.65	7.55	6.99	5.06	7.44	3.36	4.74	3.13
May	2.35	5.71	4.57	3.41	3.06	3.58	3.95	2.08	2.53	3.05	2.01	3.21	2.23	1.90	1.20	1.54
June	2.70	1.60	1.40	1.79	1.46	1.22	1.07	0.80	0.78	0.60	0.61	1.85	0.79	1.15	0.53	0.98
July	3.78	1.39	0.91	2.05	0.92	1.66	1.17	0.96	1.06	0.75	0.81	0.95	0.37	1.00	0.71	0.80
Aug.	2.35	0.79	0.88	0.68	0.33	1.06	0.97	0.69	0.56	1.03	0.59	0.61	0.37	0.81	0.29	0.49
Sept.	3.35	0.45	0.75	0.45	0.44	0.68	0.59	0.68	0.28	0.53	0.40	0.55	0.82	0.89	0.30	0.42
Oct.	1.94	0.42	0.67	0.68	0.25	0.70	0.81	0.79	0.38	0.33	0.40	0.46	0.55	1.11	0.31	0.35
Nov.	2.55	0.64	0.72	0.83	0.35	0.64	0.91	0.88	0.82	0.37	0.75	0.46	0.64	1.17	0.41	0.41
Dec.	1.73	0.68	0.80	0.67	0.44	0.87	0.65	0.74	0.77	0.45	0.84	0.67	0.78	1.37	0.44	0.51
Total	**31.33**	**18.88**	**18.07**	**18.61**	**14.33**	**15.53**	**18.05**	**19.79**	**21.24**	**18.56**	**16.23**	**16.87**	**17.49**	**16.78**	**16.34**	**11.72**

XVII	XVIII	XIX	XX	XXI	XXII	XXIII	XXIV	XXV	XXVI	XXVII	XXVIII	XXIX	XXX	XXXI	XXXII	XXXIII
0.47	0.41	0.55	0.59	0.53	0.88	0.39	0.41	0.58	0.07	0.11	0.10	0.39	1.10	4.23	2.15	2.08
0.40	0.41	0.50	0.51	0.41	0.80	0.34	0.37	0.56	0.38	0.38	1.55	0.72	1.21	3.24	2.90	0.34
1.08	1.27	1.46	1.02	1.36	0.96	1.66	1.94	2.29	5.87	5.11	1.99	2.43	4.19	5.59	6.34	−0.75
1.22	1.09	1.46	1.36	1.44	1.53	1.24	1.43	0.91	1.03	1.12	0.55	1.32	4.58	7.01	6.11	0.90
1.97	2.08	2.33	2.05	2.68	1.95	2.19	3.36	1.59	1.11	1.19	0.73	1.37	4.28	8.53	7.21	1.32
1.47	1.65	1.40	1.94	1.55	1.92	1.55	1.22	0.93	0.60	0.35	0.44	0.61	3.00	4.87	6.99	−2.12
0.67	0.51	0.79	0.95	0.86	0.75	0.62	0.73	0.81	0.33	0.17	0.42	0.38	1.53	2.95	4.23	−1.28
0.83	1.10	1.27	1.11	0.82	0.47	0.65	0.78	0.82	0.30	0.14	0.15	0.29	1.13	3.28	2.92	0.36
0.91	0.91	1.07	1.18	0.82	0.35	0.57	0.56	0.68	0.11	0.14	0.15	0.33	1.15	3.82	−0.66	4.48
1.07	1.02	1.10	0.93	0.83	0.34	0.57	0.70	0.73	0.12	0.17	0.21	0.31	1.70	4.84	0.16	4.68
1.35	1.67	1.29	1.29	1.26	0.68	0.89	1.06	0.80	0.13	0.22	0.37	0.52	2.51	5.43	2.24	3.19
1.09	0.99	1.09	0.90	1.08	0.76	0.65	1.05	0.85	0.22	0.38	0.92	1.12	2.77	5.76	4.60	1.16
12.53	**13.11**	**14.31**	**13.83**	**13.64**	**11.39**	**11.32**	**13.61**	**11.55**	**10.27**	**9.48**	**7.58**	**9.79**	**29.15**	**59.55**	**45.19**	**14.36**
0.81	0.51	0.90	0.72	0.77	0.83	0.53	0.60	0.71	0.24	0.22	0.88	1.14	2.64	3.88	−0.58	4.46
0.56	0.36	0.64	0.67	0.54	0.78	0.46	0.52	0.64	0.27	0.47	0.54	0.57	1.58	3.72	2.83	0.89
1.31	0.99	1.91	1.22	1.66	0.92	1.61	2.05	1.99	1.51	2.13	3.00	4.21	4.70	7.37	4.82	2.55
2.74	2.49	2.59	2.70	2.59	1.75	2.23	2.00	1.22	1.51	1.23	1.42	1.25	5.42	8.43	7.71	0.72
1.70	1.72	1.68	1.67	1.90	1.36	1.59	1.66	1.22	1.40	1.12	1.98	1.10	4.14	7.04	7.78	−0.74
1.16	1.46	1.48	1.33	1.73	0.94	1.32	1.93	1.40	0.28	0.31	0.60	0.30	2.43	4.76	5.68	−0.92
0.71	0.85	0.76	1.11	1.11	0.80	0.91	0.93	0.84	0.13	0.16	0.16	0.27	1.37	3.53	1.22	2.31
0.48	0.42	0.68	0.75	0.92	0.71	1.11	1.48	0.98	0.13	0.15	0.13	0.24	1.15	3.19	0.98	2.21
0.47	0.44	0.59	0.72	0.71	0.59	0.61	0.83	0.76	0.14	0.15	0.11	0.22	1.04	4.48	−0.46	4.94
0.72	1.24	0.97	0.75	0.93	0.61	0.74	1.03	0.81	0.43	0.36	0.19	0.37	1.82	6.02	2.55	3.47
1.48	1.92	1.96	1.64	1.95	0.86	1.46	1.81	1.12	0.73	0.53	0.25	0.79	3.14	6.23	0.44	5.79
0.63	0.70	0.93	0.75	0.84	0.93	0.71	0.72	0.87	0.27	0.20	0.30	0.78	2.25	3.73	−1.19	4.92
12.77	**13.10**	**15.09**	**14.03**	**15.65**	**11.08**	**13.28**	**15.56**	**12.56**	**7.04**	**7.03**	**9.56**	**11.24**	**31.68**	**62.38**	**31.78**	**30.60**
0.51	0.56	0.78	0.72	0.76	0.91	0.48	0.65	0.82	0.31	0.25	0.13	0.35	1.43	2.95	0.15	2.80
0.44	0.46	0.74	0.56	0.76	0.83	0.41	0.54	0.69	0.21	0.26	0.38	0.37	1.17	1.97	2.08	−0.11
1.40	1.59	2.16	1.36	1.90	1.21	1.89	2.78	1.78	4.32	3.37	2.17	1.86	3.96	7.31	4.69	2.62
2.80	1.92	1.95	1.96	2.18	2.35	2.39	1.96	1.33	1.28	1.13	2.19	1.17	5.63	8.35	8.19	0.16
1.61	1.22	1.33	1.49	1.23	1.19	1.28	1.41	1.08	0.55	0.53	1.79	0.60	3.58	4.93	6.27	−1.34
1.15	1.76	1.74	1.62	1.13	0.82	1.23	1.34	1.06	0.42	1.16	0.70	0.48	2.40	6.29	4.54	1.75
1.27	1.48	1.07	1.06	0.81	0.82	0.93	1.01	1.04	0.15	0.23	0.26	0.33	1.96	4.31	5.04	−0.73
0.73	1.18	0.92	0.97	0.62	0.49	0.52	0.65	0.90	0.15	0.21	0.14	0.26	1.15	3.44	3.01	0.43
0.58	0.67	0.84	0.90	0.67	0.43	0.53	0.67	0.84	0.12	0.18	0.15	0.37	0.96	3.41	0.95	2.46
0.50	0.71	0.75	0.69	0.74	0.45	0.62	0.71	0.81	0.17	0.17	0.18	0.37	1.02	2.93	−0.58	3.51
0.56	1.14	0.79	0.69	0.88	0.63	0.79	1.02	0.96	0.40	0.39	0.23	0.43	1.36	3.69	0.17	3.52
0.71	0.76	0.91	0.58	0.72	0.74	0.78	1.31	0.78	0.43	0.66	0.36	1.01	1.80	5.62	0.70	4.92
12.26	**13.45**	**13.98**	**12.60**	**12.40**	**10.87**	**11.85**	**14.05**	**12.09**	**8.51**	**8.54**	**8.68**	**7.60**	**26.42**	**55.20**	**35.21**	**19.99**
0.57	0.52	0.68	0.73	0.72	0.80	0.60	0.79	0.83	0.34	0.93	0.61	1.05	1.72	2.68	1.06	1.62
0.41	0.42	0.55	0.77	0.58	0.75	0.47	0.58	0.92	0.33	0.37	0.58	0.32	1.13	2.40	1.18	1.22
1.20	1.35	2.42	1.64	1.76	0.95	1.26	1.74	1.20	1.14	1.11	1.07	2.35	3.47	7.42	4.35	3.07
2.84	3.09	2.81	2.93	2.36	1.28	1.76	1.85	1.24	2.66	2.14	1.11	2.19	5.10	8.81	9.12	−0.31
2.12	2.01	1.96	2.24	1.92	1.42	1.75	1.30	1.06	0.71	0.61	0.66	0.85	3.45	5.02	5.89	−0.87
0.85	0.78	1.10	1.17	0.75	0.81	0.85	0.89	0.78	0.20	0.21	0.19	0.29	1.94	3.45	4.11	−0.66
0.51	0.64	0.72	0.77	0.63	0.44	0.51	0.51	0.58	0.12	0.12	0.11	0.26	1.01	3.48	1.45	2.03
0.50	0.87	0.85	0.70	0.72	0.29	0.49	0.46	0.61	0.11	0.14	0.16	0.37	0.94	5.26	−0.19	5.45
0.61	0.90	0.77	0.87	0.94	0.26	0.54	0.47	0.68	0.17	0.42	0.17	0.41	0.96	5.10	1.50	3.60
0.60	0.55	0.76	0.70	0.80	0.28	0.55	0.50	0.70	0.25	0.44	0.20	0.62	1.29	4.59	1.34	3.25
0.45	0.83	0.75	0.54	0.69	0.53	0.49	0.49	0.64	0.25	0.60	0.57	0.93	1.37	3.84	1.11	2.73
0.49	0.68	0.75	0.58	0.76	0.59	0.69	0.66	0.74	0.45	1.11	1.08	1.72	2.03	5.45	1.08	4.37
11.15	**12.64**	**14.12**	**13.64**	**12.63**	**8.40**	**9.96**	**10.24**	**9.98**	**6.73**	**8.20**	**6.51**	**11.36**	**24.41**	**57.50**	**32.00**	**25.50**
0.41	0.39	0.44	0.55	0.59	0.67	0.44	0.34	0.61	0.16	0.27	0.81	0.66	1.33	2.92	−0.33	3.25
0.34	0.36	0.41	0.59	0.54	0.62	0.37	0.42	0.54	0.31	1.31	0.44	0.94	1.24	4.06	1.82	2.24
0.79	0.70	0.97	1.34	1.67	1.18	1.01	1.29	1.33	3.86	2.63	1.54	3.01	2.85	5.51	6.01	−0.50
3.70	3.27	4.74	4.14	5.64	2.98	4.56	5.13	2.46	2.31	1.81	3.39	2.89	8.41	11.92	9.92	2.00
2.12	2.39	2.03	2.13	1.89	2.22	1.63	1.45	1.19	0.50	0.48	1.19	1.09	5.29	7.64	9.49	−1.85
1.32	1.27	1.45	1.14	1.43	1.22	1.50	1.96	1.52	0.52	0.47	0.31	1.60	2.72	5.42	5.08	0.34
1.24	1.04	1.29	1.16	1.73	0.80	1.34	1.28	1.02	0.26	0.27	0.17	0.53	2.10	5.88	5.21	0.67
0.58	0.36	0.78	0.72	0.86	0.68	0.78	1.01	0.94	0.14	0.17	0.12	0.30	1.35	3.70	2.76	0.94
0.82	1.06	1.05	1.07	0.94	0.53	0.78	0.87	0.85	0.22	0.36	0.12	0.68	1.33	4.68	1.23	3.45
0.52	0.45	0.80	0.65	0.78	0.56	0.57	0.62	0.79	0.17	0.21	0.19	0.48	1.10	3.04	−1.44	4.48
0.64	0.57	0.97	0.66	0.95	0.56	0.72	0.91	0.87	0.19	0.36	0.23	0.50	1.31	3.86	−1.85	5.71
0.51	0.51	0.72	0.60	0.78	0.65	0.61	0.74	0.77	0.11	0.18	0.25	0.52	1.28	3.01	−2.37	5.38
12.99	**12.37**	**15.65**	**14.75**	**17.80**	**12.67**	**14.31**	**16.02**	**12.89**	**8.75**	**8.52**	**8.76**	**13.20**	**30.31**	**61.64**	**35.53**	**26.11**

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI
1923																
Jan.	1.79	0.51	0.87	0.47	0.39	1.03	0.67	0.56	0.57	0.68	0.76	0.85	0.52	2.41	0.39	0.42
Feb.	1.32	0.35	0.79	0.28	0.47	1.07	0.56	0.27	0.46	0.62	0.59	0.84	0.28	2.78	0.29	0.29
Mar.	2.96	0.30	0.87	0.37	0.49	0.98	0.50	0.54	0.70	0.57	1.19	1.63	0.40	1.77	3.12	2.63
April	2.18	1.81	0.77	2.53	1.30	1.19	1.58	6.03	7.61	3.99	4.46	3.34	6.29	1.23	5.42	5.14
May	2.64	4.66	2.67	4.77	4.42	1.97	3.30	5.37	7.49	6.82	5.52	4.92	5.85	0.93	2.73	2.86
June	2.34	2.12	1.22	1.83	1.50	2.24	1.71	1.55	2.01	2.23	1.74	2.47	2.19	0.91	0.79	0.84
July	2.36	1.09	0.98	1.79	0.71	1.87	1.14	0.63	0.51	0.39	0.43	2.02	0.62	(0.60)	0.32	0.41
Aug.	3.33	0.62	0.85	0.44	0.41	1.32	1.02	0.76	0.32	0.20	0.37	0.72	0.34	(0.45)	0.23	0.30
Sept.	2.83	0.58	0.73	0.46	0.87	1.78	1.15	0.74	0.66	0.36	0.37	0.53	0.35	(0.35)	0.25	0.35
Oct.	3.36	0.46	0.85	0.35	0.38	1.42	—	—	0.37	0.31	0.30	0.45	0.29	0.91	0.23	0.30
Nov.	1.26	0.43	0.78	0.35	0.36	0.80	—	—	0.64	0.75	0.95	0.47	0.44	0.99	0.41	0.42
Dec.	2.25	0.47	0.58	0.46	0.41	0.74	—	—	1.98	1.16	2.04	0.92	2.21	1.14	0.89	0.99
Total	**28.62**	**13.40**	**11.96**	**14.10**	**11.71**	**16.41**	—	—	**23.32**	**18.08**	**18.72**	**19.16**	**19.78**	**14.47**	**15.07**	**14.95**
1924																
Jan.	2.43	0.55	0.65	0.39	0.44	0.87	—	—	0.91	1.18	1.46	1.60	1.48	1.22	0.97	1.21
Feb.	1.90	0.47	0.68	0.24	0.76	0.94	—	—	0.80	0.85	0.90	1.32	1.01	1.00	0.88	0.83
Mar.	1.80	0.49	0.75	0.33	0.57	0.94	—	—	1.26	1.27	1.61	1.85	1.80	1.45	2.65	2.86
April	2.27	1.23	0.70	3.04	3.08	1.78	—	—	6.52	3.60	4.56	3.11	4.90	2.89	4.82	4.07
May	3.22	2.71	0.99	1.90	2.50	1.21	—	—	7.11	4.19	4.20	4.69	3.94	2.18	3.20	3.11
June	2.91	1.63	0.95	0.97	1.31	1.27	—	—	1.95	1.92	1.18	2.61	1.58	1.35	1.42	0.80
July	3.23	0.77	0.68	2.33	0.52	1.86	—	—	0.48	1.92	0.81	1.86	0.51	1.21	0.71	0.57
Aug.	4.67	0.65	0.69	0.90	0.38	1.07	—	—	0.39	0.51	0.29	0.64	0.41	1.01	0.89	0.49
Sept.	2.42	0.52	0.65	0.47	0.28	0.80	—	—	0.33	0.40	0.26	0.39	0.30	1.17	0.49	0.36
Oct.	0.34	0.40	0.68	0.38	0.29	0.74	—	—	0.50	0.38	0.43	0.35	0.29	1.27	0.50	0.38
Nov.	1.96	0.67	0.54	0.95	0.61	0.93	—	—	0.53	0.34	0.30	0.39	0.34	1.26	0.36	0.30
Dec.	2.32	0.71	0.64	0.77	0.55	0.91	—	—	1.26	0.74	1.16	0.64	0.50	1.29	1.44	0.85
Total	**29.47**	**10.80**	**8.60**	**12.67**	**11.29**	**13.32**	—	—	**22.04**	**17.30**	**17.16**	**19.45**	**17.06**	**17.30**	**18.33**	**15.83**
1925																
Jan.	1.01	0.42	0.65	0.41	0.45	0.99	—	—	0.57	0.60	0.47	0.61	0.29	1.12	0.49	0.47
Feb.	1.53	0.38	0.58	0.39	0.58	0.91	—	—	0.88	0.62	1.23	0.65	0.58	1.29	2.08	1.82
Mar.	1.60	0.51	0.72	0.91	0.68	1.09	—	—	1.65	1.64	2.35	1.53	3.66	2.37	4.53	3.87
April	1.96	1.50	0.65	3.62	2.73	1.67	—	—	8.65	4.99	5.26	4.51	4.36	1.67	2.53	1.89
May	1.20	1.61	0.68	1.68	1.10	1.57	—	—	2.70	2.58	1.95	2.09	3.32	1.66	0.88	0.68
June	3.01	1.82	0.81	1.16	1.33	1.90	—	—	2.28	2.07	1.27	2.05	0.83	1.43	0.61	0.48
July	2.95	1.01	0.78	0.69	0.80	1.79	—	—	1.02	0.98	0.67	0.71	0.65	1.30	0.50	0.40
Aug.	1.49	0.68	0.78	0.42	0.40	0.73	—	—	0.37	0.42	0.33	1.22	0.40	1.13	0.32	0.29
Sept.	3.30	0.50	0.74	0.40	0.22	0.63	—	—	0.25	0.45	0.38	0.39	0.32	1.04	0.28	0.35
Oct.	2.98	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Nov.	1.98	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Dec.	1.92	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Total	**24.93**	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

XVII	XVIII	XIX	XX	XXI	XXII	XXIII	XXIV	XXV	XXVI	XXVII	XXVIII	XXIX	XXX	XXXI	XXXII	XXXIII
0.47	0.47	0.56	0.50	0.52	0.85	0.51	0.45	0.59	.10	0.24	0.22	0.37	1.26	3.05	1.81	1.24
0.37	0.37	0.50	0.44	0.49	0.80	0.43	0.44	0.51	.12	0.32	0.31	0.31	1.12	2.44	-1.74	4.18
0.46	0.40	0.61	0.86	0.66	1.09	0.68	0.66	0.95	1.74	1.68	1.46	3.25	2.25	5.21	5.12	0.09
2.04	1.82	2.66	1.87	3.06	1.66	2.97	4.33	2.56	4.02	3.48	0.70	3.20	5.69	7.87	5.67	2.20
1.78	2.05	1.78	1.90	1.60	1.54	1.74	1.26	0.97	0.33	0.51	0.93	2.40	5.77	8.41	8.27	0.14
1.33	2.22	1.56	1.93	1.56	0.83	1.12	0.72	0.80	0.14	0.38	0.66	0.73	2.65	4.99	5.66	-0.67
0.89	1.03	0.93	1.02	0.81	0.59	0.76	0.89	0.90	0.11	0.14	0.16	0.34	1.63	3.99	3.98	0.01
0.46	0.51	0.59	0.52	0.57	0.35	0.46	0.53	0.70	0.11	0.11	0.50	0.19	1.02	4.35	1.17	3.18
0.55	0.58	0.66	0.65	0.65	0.36	0.52	0.67	0.73	0.12	0.19	0.98	0.33	1.15	3.98	2.00	1.98
0.44	0.46	0.64	0.58	0.64	0.43	0.48	0.56	0.69	0.18	0.35	0.87	0.41	1.06	4.42	-0.21	4.63
0.45	0.46	0.62	0.50	0.59	0.45	0.45	0.53	0.62	0.20	0.26	0.89	0.38	0.98	2.24	-0.79	3.03
0.44	0.43	0.63	0.46	0.66	0.61	0.48	0.56	0.67	0.17	0.35	1.58	0.47	1.31	3.56	-0.77	4.33
9.68	**10.80**	**11.74**	**11.23**	**11.81**	**9.56**	**10.60**	**11.60**	**10.69**	**7.34**	**8.01**	**9.26**	**12.38**	**25.89**	**54.51**	**30.17**	**24.34**
0.34	0.36	0.49	0.46	0.49	0.71	0.44	0.47	0.48	0.10	0.16	1.08	0.39	1.29	3.72	-0.84	4.56
0.35	0.31	0.53	0.39	0.48	0.72	0.37	0.34	0.69	0.18	0.34	1.25	0.46	2.53	4.43	4.21	0.22
0.40	0.36	0.57	0.80	0.57	0.80	0.56	0.40	0.85	1.36	1.78	2.31	1 61	4.49	6.29	2.37	3.92
1.61	1.86	2.40	2.44	2.74	1.42	2.53	3.94	2.13	3.74	2.16	2.00	1.52	4.30	6.57	5.58	0.99
2.21	2.64	2.56	3.12	3.09	2.27	2.73	2.17	1.37	2.06	1.52	0.73	1.19	4.81	8.03	6.50	1.53
0.73	0.97	1.34	1.24	1.03	0.99	1.20	1.35	1.04	0.76	0.50	1.40	0.27	2.21	5.12	5.01	0.11
0.63	0.77	1.06	0.86	0.85	0.84	0.80	0.95	0.92	(1.00)	0.30	1.01	0.19	1.65	4.88	4.20	0.68
0.92	1.53	1.36	1.43	0.91	1.80	1.46	2.40	1.71	(2.25)	4.66	0.35	0.40	2.40	7.07	4.92	2.15
0.55	0.62	0.78	0.75	0.67	1.02	1.00	1.24	1.15	(1.60)	0.46	0.18	0.19	1.40	3.82	1.85	1.97
0.56	0.51	0.74	0.52	0.69	0.85	0.68	0.86	0.95	....	—	0.17	—	1.31	1.65	0.06	1.59
0.48	0.55	0.80	0.45	0.70	0.76	0.63	0.92	0.98	....	—	0.17	—	1.32	3.28	-3.29	6.57
0.41	0.41	0.50	0.34	0.57	0.79	0.52	0.53	0.83	....	—	0.22	—	1.34	3.66	-1.17	4.83
9.19	**10.89**	**13.13**	**12.80**	**12.79**	**12.97**	**12.92**	**15.57**	—	....	—	—	—	**29.05**	**58.52**	**29.40**	**29.12**
0.37	0.33	0.52	0.39	0.45	0.84	0.40	0.47	0.67	....	—	0 19	—	1.16	2.17	—	—
0.33	0.32	0.49	0.40	0.54	0.73	0.50	0.50	0.74	....	—	0.67	—	1.30	2.83	—	—
0.46	0.47	0.78	0.71	0.81	0.85	0.85	0.86	1.26	....	—	0.98	—	2.02	3.62	—	—
0.87	0.97	1.32	0.95	1.06	0.47	1.06	1.61	1.04	....	—	0.49	—	2.68	4.64	—	—
0.68	0.68	0.87	0.68	0.71	0.48	0.72	0.97	0.81	....	—	0.32	—	1.88	3.08	—	—
0.70	1.29	1.12	1.13	0.95	0.73	1.34	2.10	1.13	....	—	0.16	—	2.22	5.23	—	—
0.38	0.38	0.47	0.47	0.51	0.92	0.64	0.93	1.11	....	—	0.18	—	1.55	4.50	—	—
0.33	0.56	0.61	0.53	0.48	0.57	0.46	0.81	0.89	....	—	0.14	—	1.11	2.60	—	—
0.44	0.82	0.52	0.52	0.47	0.38	0.41	0.75	0.82	....	—	0.15	—	0.96	4.26	—	—
—	—	—	—	—	—	—	—	—	....	—	—	—	—	—	—	—
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—	—	—	—	—	—	—	—	—		—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	....	—	—	—	—	—	—	—

LAKES ERIE AND ST. CLAIR—APPROXIMATE EVAPORATION LOSS

Measured inflow from gaugings of local tributaries

Plus rainfall on surface of lake

Minus outflow gauged in Niagara River, corrected for ice, diversions and rise or fall of lake

Minus inflow from Lake Huron.

Date, Year and Month	Estimated Rainfall, Inches Depth on Lake Surface	Inflow from Local Tributaries: Canadian: Thames River at Kilworth,* Drainage Area = 1270 Sq. Mi.	Canadian: Grand River at York, Drainage† Area = 2280 Sq. Mi.	American: Huron River at Barton, Drainage Area = 723 Sq. Mi.	American: Auglaize River at Defiance, Drainage Area = 2320 Sq. Mi.	American: Cattaraugus Creek at Versailles, Drainage Area = 467 Sq. Mi.	Total Weighted Average Inflow from local tributaries, Inches Depth on Lake Surface	Total Inflow from Local Tributaries Plus Rainfall on lake surface, Inches Depth on Lake. I+VII	Local Net Yield from Lake. Outflow Corrected for Rise and Fall of Lake Minus Inflow from Lake above; Inches Depth on Lake	Computed Evaporation or Loss between Inflow and Outflow; Inches Depth on Lake Surface. VIII—IX
		Inches Depth on Drainage Area								
	I	II	III	IV	V	VI	VII	VIII	IX	X
1915										
January	3.1	1.18	0.40	0.56	(0.98)	2.73	2.88	5.98	4.37	1.61
February	2.7	2.62	0.88	1.54	(2.05)	4.01	5.80	8.50	6.87	1.63
March	1.1	1.33	1.93	1.14	(1.10)	1.34	3.90	5.00	6.32	−1.32
April	0.8	1.08	1.99	0.62	0.22	1.54	2.54	3.34	2.68	0.66
May	3.0	0.38	0.43	0.59	0.14	0.89	1.05	4.05	4.76	−0.71
June	2.7	0.29	0.27	0.59	0.50	0.41	1.27	3.97	4.20	−0.23
July	5.8	0.46	0.28	0.56	1.72	1.41	3.19	8.99	4.99	4.00
August	5.8	1.17	1.36	0.72	2.27	0.96	4.77	10.57	6.25	4.32
September	3.9	0.69	1.15	1.13	1.43	0.54	3.41	7.31	1.62	5.69
October	1.8	0.76	0.84	0.84	0.89	2.10	2.84	4.64	0.21	4.43
November	2.3	1.05	0.81	0.62	0.46	1.51	2.12	4.42	−3.12	7.54
December	2.4	0.95	0.92	0.61	0.47	2.32	2.37	4.77	2.40	2.37
Total	**35.4**	**11.96**	**11.26**	**9.52**	**12.23**	**19.76**	**36.14**	**71.54**	**41.55**	**29.99**
1916										
January	4.3	5.78	3.83	1.42	4.55	4.50	12.07	16.37	8.37	8.00
February	2.0	1.00	1.50	1.22	1.56	0.85	4.04	6.04	12.00	−5.96
March	3.2	2.10	2.24	1.91	2.49	5.06	7.48	10.68	7.85	2.83
April	3.7	2.70	4.09	2.39	1.21	5.06	7.34	11.04	11.09	−0.05
May	5.2	2.62	2.01	1.61	1.12	3.24	5.12	10.32	8.53	1.79
June	3.8	1.58	1.99	1.17	1.19	1.80	4.29	8.09	8.51	−0.42
July	1.1	0.22	0.35	0.53	0.16	0.79	0.93	2.03	1.87	0.16
August	2.3	0.10	0.18	0.25	0.07	0.30	0.41	2.71	−3.02	5.73
September	2.5	0.91	0.16	0.21	0.03	0.22	0.60	3.10	−5.10	8.20
October	3.0	0.16	0.28	0.33	0.06	0.33	0.53	3.53	−3.66	7.19
November	2.0	0.15	0.31	0.38	0.05	0.76	0.67	2.67	−2.35	5.02
December	2.4	0.54	0.53	0.48	0.09	0.70	1.01	3.41	−0.48	3.89
Total	**35.5**	**17.86**	**17.47**	**11.90**	**12.58**	**23.61**	**44.49**	**79.99**	**43.61**	**36.38**

*Run-off of Thames River at Byron, 1230 sq. mi., used after September 1922.
†Run-off of Grand River at Galt, 1360 sq. mi., used after September 1923.

LAKES ERIE AND ST. CLAIR—APPROXIMATE EVAPORATION LOSS—Continued

	I	II	III	IV	V	VI	VII	VIII	IX	X
1917										
January	3.0	0.36	0.42	0.48	0.89	1.67	2.19	5.19	4.88	0.31
February	1.5	0.05	0.23	0.40	0.51	1.77	1.46	2.96	-0.54	3.50
March	3.3	4.13	3.57	1.09	1.73	4.78	7.59	10.89	3.53	7.36
April	3.9	2.16	2.33	1.57	2.02	2.47	6.11	10.01	14.20	-4.19
May	4.4	1.69	1.10	0.96	0.99	1.99	3.47	7.87	6.75	1.12
June	5.8	1.68	1.14	1.04	0.61	2.72	3.22	9.02	8.99	0.03
July	3.9	2.10	2.36	0.63	0.33	1.75	3.29	7.19	6.47	0.72
August	2.4	0.23	0.38	0.22	0.59	0.55	1.31	3.71	-1.61	5.32
September	1.9	0.12	0.22	0.32	0.05	0.59	0.53	2.43	-2.21	4.64
October	5.4	0.40	0.39	0.40	0.42	4.61	2.30	7.70	-3.35	11.05
November	1.1	0.40	0.42	0.49	0.47	1.72	1.67	2.77	3.54	-0.77
December	1.7	0.53	0.43	0.36	0.24	2.26	1.51	3.21	0.54	2.67
Total	**38.3**	**13.85**	**12.99**	**7.96**	**8.85**	**26.88**	**34.65**	**72.95**	**41.19**	**31.76**
1918										
January	3.2	0.65	0.18	0.26	0.15	0.73	0.83	4.03	1.03	3.00
February	2.9	1.61	2.28	2.01	2.34	3.94	6.88	9.78	0.25	9.53
March	2.6	5.07	6.55	3.69	1.59	4.67	10.57	13.17	11.55	1.62
April	2.4	1.04	1.56	0.98	0.20	1.17	2.28	4.68	9.06	-4.38
May	2.8	0.53	0.56	0.63	0.31	1.01	1.46	4.26	-2.81	7.07
June	2.4	0.28	0.35	0.25	0.24	0.56	0.87	3.27	2.73	0.54
July	1.8	0.10	0.22	0.16	0.06	0.45	0.43	2.23	-0.63	2.86
August	2.3	0.04	0.18	0.12	0.05	0.26	0.32	2.62	-1.30	3.92
September	5.1	0.32	0.55	0.21	0.27	0.60	1.06	6.16	-1.19	7.35
October	2.3	0.20	0.45	0.23	0.08	1.08	.86	3.16	-1.98	5.14
November	1.8	0.43	0.64	0.37	0.27	1.43	1.43	3.23	-1.58	4.81
December	3.0	1.52	1.46	0.78	1.71	1.82	4.46	7.46	0.88	6.58
Total	**32.6**	**11.79**	**14.98**	**9.69**	**7.27**	**17.72**	**31.45**	**64.05**	**16.01**	**48.04**
1919										
January	1.2	1.15	1.18	0.55	0.54	1.82	2.53	3.73	1.35	2.38
February	1.5	0.69	0.50	0.40	0.30	1.07	1.38	2.88	1.56	1.32
March	3.0	3.42	3.44	1.56	3.08	2.28	8.55	11.55	5.51	6.04
April	4.4	2.06	1.63	2.16	1.08	2.91	4.78	9.18	9.44	-0.26
May	5.0	2.55	2.41	1.59	0.92	4.09	5.29	10.29	10.69	-0.40
June	2.3	0.37	0.42	0.51	0.22	0.70	1.07	3.37	4.30	-0.93
July	1.4	0.08	0.23	0.31	0.19	0.33	0.64	2.04	-1.26	3.30
August	3.8	0.06	0.21	0.25	0.17	0.43	0.58	4.38	-1.06	5.44
September	2.6	0.09	0.19	0.25	0.06	0.24	0.39	2.99	-2.39	5.38
October	4.2	0.23	0.28	0.36	0.82	0.37	1.58	5.78	-1.49	7.27
November	2.0	0.51	0.43	0.55	1.15	0.81	2.38	4.38	-0.65	5.03
December	1.3	0.50	1.11	0.54	0.53	1.05	2.05	3.35	0.05	3.30
Total	**32.7**	**11.71**	**12.03**	**9.03**	**9.06**	**16.10**	**31.22**	**63 92**	**26.05**	**37.87**
1920										
January	2.0	0.20	0.25	0.30	0.10	0.43	0.58	2.58	2.64	-0.06
February	1.5	0.19	0.21	0.31	0.30	0.37	0.82	2.32	-0.56	2.88
March	1.8	4.29	4.01	1.92	1.84	6.00	8.71	10.51	2.33	8.18
April	3.7	1.56	1.86	1.20	2.45	2.04	5.93	9.63	8.82	0.81
May	1.1	0.44	0.55	0.76	0.43	0.96	1.62	2.72	8.65	-5.93
June	4.4	0.15	0.44	0.39	0.13	0.65	0.82	5.22	3.41	1.81
July	4.1	0.32	0.68	0.22	0.87	1.27	2.11	6.21	2.98	3.23
August	2.9	0.18	0.30	0.22	0.16	0.48	0.67	3.57	1.04	2.53
September	1.7	0.13	0.19	0.20	0.11	0.41	0.49	2.19	-1.89	4.08
October	3.3	0.24	0.28	0.20	0.10	0.50	0.59	3.89	-2.50	6.39
November	3.4	0.76	0.72	0.38	0.88	1.58	2.44	5.84	-0.32	6.16
December	3.2	1.63	1.58	0.74	1.28	2.44	4.15	7.35	3.00	4.35
Total	**33.1**	**10.09**	**11.07**	**6.84**	**8.65**	**17.13**	**28.93**	**62.03**	**27 60**	**34.43**

LAKES ERIE AND ST. CLAIR—APPROXIMATE EVAPORATION LOSS—Continued

	I	II	III	IV	V	VI	VII	VIII	IX	X
1921										
January	1.0	1.35	1.24	0.60	1.04	2.41	3.48	4.48	2.30	2.18
February	1.9	0.42	0.53	0.34	1.79	1.84	3.45	5.35	7.65	-2.30
March	4.1	3.47	3.86	1.24	3.35	3.38	9.36	13.46	5.64	7.82
April	4.1	2.34	2.33	1.18	1.78	2.03	5.59	9.69	11.76	-2.07
May	2.5	0.67	0.98	0.56	1.46	0.98	3.24	5.74	6.89	-1.15
June	2.5	0.29	0.52	0.35	0.22	0.46	0.96	3.46	2.40	1.06
July	3.4	0.78	0.60	0.30	0.07	0.42	0.96	4.36	1.70	2.66
August	3.3	0.16	0.27	0.25	0.04	0.34	0.46	3.76	-1.62	5.38
September	3.4	0.17	0.24	0.57	0.04	0.24	0.55	3.95	-0.97	4.92
October	3.1	0.44	0.56	0.52	0.07	0.55	0.93	4.03	-2.92	6.95
November	3.3	0.81	0.71	0.86	1.28	3.70	3.72	7.02	2.69	4.33
December	2.4	2.11	1.18	1.09	1.13	1.92	3.89	6.29	3.45	2.84
Total	**35.0**	**13.01**	**13.02**	**7.86**	**12.27**	**18.27**	**36.59**	**71.59**	**38.97**	**32.62**
1922										
January	1.7	0.83	0.44	0.64	0.60	1.53	2.01	3.71	4.02	-0.31
February	1.9	1.92	1.20	0.70	0.96	2.32	3.54	5.44	1.63	3.81
March	3.6	1.97	3.45	1.30	2.55	3.63	7.63	11.23	5.04	6.19
April	2.9	3.79	4.42	2.50	4.29	2.66	11.37	14.27	15.01	-0.74
May	2.5	0.46	0.48	1.05	2.75	1.05	4.78	7.28	8.10	-0.82
June	3.2	0.85	0.70	0.40	0.37	1.52	1.77	4.97	4.64	0.33
July	3.2	0.29	0.28	0.22	0.31	1.05	1.05	4.25	1.02	3.23
August	3.3	0.21	0.24	0.19	0.06	0.99	0.64	3.94	-0.90	4.84
September	3.1	0.28	0.46	0.24	0.41	0.46	1.14	4.24	-0.24	4.48
October	1.9	0.24	0.23	0.27	0.06	0.47	0.53	2.43	-3.12	5.55
November	1.7	0.22	0.22	0.29	0.04	0.59	0.53	2.23	-3.35	5.58
December	2.2	0.22	0.31	0.29	0.25	0.95	0.96	3.16	-1.27	4.43
Total	**31.2**	**11.28**	**12.43**	**8.09**	**12.65**	**17.22**	**35.95**	**67.15**	**30.58**	**36.57**
1923										
January	2.8	0.47	0.36	0.32	1.90	1.97	3.53	6.33	5.55	0.78
February	1.6	0.20	0.25	0.27	0.78	1.58	1.78	3.38	3.41	-0.03
March	2.8	4.07	2.41	1.31	2.69	4.52	8.14	10.94	5.63	5.31
April	2.4	2.66	2.86	0.71	0.72	1.80	4.37	6.77	8.84	-2.07
May	3.1	1.84	1.74	0.54	1.76	1.13	4.53	7.63	6.45	1.18
June	2.5	0.57	0.53	0.26	0.17	0.37	0.94	3.44	4.73	-1.29
July	2.7	0.20	0.21	0.20	0.18	0.29	0.60	3.30	2.23	1.07
August	2.4	0.19	0.18	0.15	0.10	0.19	0.41	2.81	-1.52	4.33
September	3.2	0.38	0.23	0.19	0.10	0.19	0.53	3.73	-0.60	4.33
October	1.7	0.24	0.21	0.22	0.06	—	0.40	2.10	-1.81	3.91
November	2.4	0.39	0.25	0.26	0.06	—	0.51	2.91	-1.49	4.40
December	4.2	2.71	1.03	0.51	1.99	—	5.00	9.20	7.53	1.67
Total	**31.8**	**13.92**	**10.26**	**4.94**	**10.51**	—	**30.74**	**62.54**	**38.95**	**23.59**
1924										
January	3.5	1.75	0.88	0.44	1.44	—	3.62	7.12	7.02	0.10
February	2.4	0.64	0.36	0.40	1.03	—	2.22	4.62	8.41	-3.79
March	2.0	3.63	2.02	1.37	2.57	—	7.20	9.20	2.68	6.52
April	2.6	2.57	3.50	1.17	1.41	—	5.60	8.20	10.82	-2.62
May	3.4	1.95	2.38	0.75	0.77	—	3.60	7.00	8.95	-1.95
June	3.9	0.37	0.43	0.58	2.16	—	3.94	7.84	5.99	1.85
July	2.9	0.30	0.27	0.39	0.46	—	1.15	4.05	6.26	-2.21
August	2.3	0.41	0.27	0.18	0.06	—	0.50	2.80	-0.12	2.92
September	4.9	0.22	0.17	0.19	0.14	—	0.49	5.39	0.37	5.02
October	0.6	*0.16	0.26	0.20	0.05	—	0.37	0.97	0.12	0.85
November	1.3	0.15	0.15	0.18	0.02	—	0.27	1.57	-4.47	6.04
December	3.1	0.26	0.23	0.27	0.95	—	1.80	4.90	1.31	3.59
Total	**32.9**	**12.41**	**10.92**	**6.12**	**11.06**	—	**30.76**	**63.66**	**47.34**	**16.32**

*From October 1924 to September 1925 the average of run-off for the Thames River at Ealing and at Fanshawe is used.

These hundreds of measurements of evaporation by the monthly differences between inflow and outflow for each lake are brought together in the following tables for closer comparison.

The values found month after month and year after year **are so remarkably consistent that they seem to prove beyond all reasonable doubt that evaporation from these lakes is greater in January and February than in May and June, etc.**

EVAPORATION ESTIMATED FROM STREAM GAUGING AND RAINFALL ON LAKES

The following table gives a summary of the monthly values of evaporation from the Great Lakes above Niagara, deduced from inflow minus outflow as computed in the preceding pages 68 to 78.

Monthly Difference between Inflow and Outflow for Lake Superior

Date Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1920	..	..	..	..	..	..	..	−0.51	1.46	2.34	2.50	4.44	—
1921	2.28	3.84	3.80	3.38	−0.61	−1.62	1.96	−0.13	2.09	2.49	4.06	3.65	25.19
1922	4.48	3.98	2.63	1.88	−0.40	0.64	−0.66	−0.67	0.58	2.85	4.57	3.84	23.72
1923	3.83	2.14	2.59	2.80	−0.40	1.51	0.83	−0.43	1.08	2.80	1.71	2.53	20.99
1924	2.72	3.55	2.35	3.23	1.26	0.70	1.60	1.54	−0.66	−0.12	2.44	4.43	23.04
1925	4.28	1.86	1.77	0.02	0.74	−0.62	−0.66	−0.18	3.39	—	—	—	—
Average	**3.52**	**3.07**	**2.63**	**2.26**	**0.08**	**0.12**	**0.61**	**−0.06**	**1.32**	**2.07**	**3.06**	**3.78**	**22.46**

Monthly Difference between Inflow and Outflow for Lakes Michigan and Huron

Date Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1915	3.14	−0.18	2.59	2.72	0.63	0.79	0.87	−0.13	5.68	3.28	6.96	2.13	28.49
1916	6.81	0.84	2.07	2.59	0.08	0.07	−1.23	4.18	7.94	5.96	1.30	4.91	35.52
1917	3.30	1.51	0.99	1.90	0.02	−0.03	−1.61	0.34	1.83	5.51	1.48	5.46	20.70
1918	2.08	0.34	−0.75	0.90	1.32	−2.12	−1.28	0.36	4.48	4.68	3.19	1.16	14.36
1919	4.46	0.89	2.55	0.72	−0.74	−0.92	2.31	2.21	4.94	3.47	5.79	4.92	30.60
1920	2.80	−0.11	2.62	0.16	−1.34	1.75	−0.73	0.43	2.46	3.51	3.52	4.92	19.99
1921	1.62	1.22	3.07	−0.31	−0.87	−0.66	2.03	5.45	3.60	3.25	2.73	4.37	25.50
1922	3.25	2.24	−0.50	2.00	−1.85	0.34	0.67	0.94	3.45	4.48	5.71	5.38	26.11
1923	1.24	4.18	0.09	2.20	0.14	−0.67	0.01	3.18	1.98	4.63	3.03	4.33	24.34
1924	4.56	0.22	3.92	0.99	1.53	0.11	0.68	2.15	1.97	1.59	6.57	4.83	29.12
Average	**3.33**	**1.12**	**1.66**	**1.39**	**−0.11**	**−0.13**	**0.17**	**1.91**	**3.83**	**4.04**	**4.03**	**4.24**	**25.47**

Monthly Difference between Inflow and Outflow for Lake Erie

Date Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1915	1.61	1.63	−1.32	0.66	−0.71	−0.23	4.00	4.32	5.69	4.43	7.54	2.37	29.99
1916	8.00	−5.96	2.83	−0.05	1.79	−0.42	0.16	5.73	8.20	7.19	5.02	3.89	36.38
1917	0.31	3.50	7.36	−4.19	1.12	0.03	0.72	5.32	4.64	11.05	−0.77	2.67	31.76
1918	3.00	9.53	1.62	−4.38	7.07	0.54	2.86	3.92	7.35	5.14	4.81	6.58	48.04
1919	2.38	1.32	6.04	−0.26	−0.40	−0.93	3.30	5.44	5.38	7.27	5.03	3.30	37.87
1920	−0.06	2.88	8.18	0.81	−5.93	1.81	3.23	2.53	4.08	6.39	6.16	4.35	34.43
1921	2.18	−2.30	7.82	−2.07	−1.15	1.06	2.66	5.38	4.92	6.95	4.33	2.84	32.62
1922	−0.31	3.81	6.19	−0.74	−0.82	0.33	3.23	4.84	4.48	5.55	5.58	4.43	36.57
1923	0.78	−0.03	5.31	−2.07	1.18	−1.29	1.07	4.33	4.33	3.91	4.40	1.67	23.59
1924	0.10	−3.79	6.52	−2.62	−1.95	1.85	−2.21	2.92	5.02	0.85	6.04	3.59	16.32
Average	**1.80**	**1.06**	**5.06**	**−1.49**	**0.02**	**0.28**	**1.90**	**4.47**	**5.41**	**5.87**	**4.81**	**3.57**	**32.76**

Note the irregularity, during the winter months, in the amount of evaporation from Lakes Michigan-Huron and Erie, as estimated from inflow minus outflow in the preceding tables.

This is largely due to errors in making proper allowance for ice retardation in the discharges from Lakes Huron and Erie.

Obviously, any over estimate of the quantity of flow through the St. Clair and Detroit Rivers when ice-jams and gorges were holding water back in Lakes Huron and Michigan would result in an apparent excess of evaporation from Lake Erie and produce an opposite effect for Lakes Michigan–Huron.

Although in comparisons made from month to month the discrepancies appear large, these are mostly balanced and eliminated in the yearly totals and especially so in the final grand average covering many years.

EVAPORATION FROM THE GREAT LAKES
ESTIMATED FROM METEOROLOGICAL DATA

The computations of the two preceding chapters have resulted in some strange and unexpected relations of negative yield of certain of the Great Lakes during a part of the year, and of a varying quantity of water lost between the inflow and the outflow of each lake such that after making due allowance for errors of observation, these remarkable differences between inflow and outflow can **only be explained by abnormally large evaporation in winter and abnormally small evaporation in summer.**

It is contrary to all precedent to find the evaporation far greater in mid-winter than in summer, but the following described studies show that this curious state of affairs is true for some of the Great Lakes. The two entirely independent studies, the hydrographic study which precedes and the meteorologic study which follows, confirm each other most remarkably, particularly in the case of Lake Superior, where, although the conditions are more extreme, there are fewer complications with the discharge from other lakes or with obstructions of lake discharge by ice.

The following study of evaporation loss is entirely independent of that in the preceding chapter and from an entirely different line of data.

As has been already stated on page 24, there are long periods within which the quantity of water which goes up into the air in evaporation out of the Great Lakes, is greater than the quantity of water which flows out from the lakes, down the Niagara or St. Lawrence Rivers.*

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*Note—The probable evaporation in the three months August, September and October, from the water surface of all of the Great Lakes is about 12 inches depth.

$$\frac{\text{12 inches x 87,620 sq. m. x 27,800,000 sq. ft.}}{\text{12 in. x 92 days x 24 hrs. x 3600 sec. per hr.}} \text{ or 309,000 cu. ft. sec. above Niagara}$$

which is 1½ times the average discharge of the Niagara River.

The probable evaporation for the year for all lakes above Niagara is at least

$$\frac{\text{2.2 ft. depth x 87,620 sq. miles x 27,800,000 sq. ft.}}{\text{365¼ days x 86,400 sec. per day}} = \text{170,000 cu. ft. per second}$$

which is $\frac{\text{170,000 c.f.s.}}{\text{207,900 c.f.s.}}$ or 82.0% of the average flow of the Niagara River.

The probable evaporation throughout the year from all the Great Lakes is at least

$$\frac{\text{2.25 ft. depth x 95,150 sq. miles x 27,800,000 sq. ft. per sq. mile.}}{\text{365¼ days x 86,400 sec.}} = \text{188,000 cu. ft. sec.}$$

which is $\frac{\text{188,000 c.f.s.}}{\text{232,240 c.f.s.}}$ or 81.0% of average flow in St. Lawrence River.

Moreover, this quantity evaporated varies greatly from day to day according to the direction and dryness of the wind, also the temperature of the air and water in contact. On some days within the same week, and all without rainfall, probably this evaporation loss is four times as great as upon others days, † and there is reason to believe that in some years this loss by evaporation may be much larger than in other years, and that **an excess of evaporation in recent years may account in part for the present low levels of the lakes.**

A small rise in the average temperature of the air and water in the summer months combined with a slightly lower temperature of air in winter, could make a noteworthy change in the mean annual evaporation and run-off from the Great Lakes.

If this change were for a single degree each way the computed effect in the flow of the Niagara River would be a loss of about 8,000 cu. ft. per sec.

There are several other strange and interesting facts found when evaporation from the Great Lakes is closely investigated. For example, the evaporation from Lake Superior which is remarkably small in summer, commonly carries off into the air in the three winter months more water than flows in from all of the tributaries to this lake, so that unless this lake were drawn down, thus taking water from storage, commonly there would be no discharge down the St. Marys River from the middle of December to the middle of March.

The northern ends of Michigan and Huron are much like Superior, and their southern ends much like Erie, in monthly depth of evaporation.

Notwithstanding the impossibility of changing the rate of evaporation by any human contrivances, it is important to find out all that can be learned about its total quantity, its variable rate from day to day, from month to month and from year to year; and to find out the part taken by each of the various causes which produce these changes; all as an aid to future forecasting and regulation of the discharge and levels of the lakes, for the future benefit of navigation and power.

Such accumulated records will some time have a value to the engineer-forecaster, somewhat similar to the value which the 65 years of records of lake heights now available, have to the designing engineer.

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†Mr. Fitzgerald found, at Boston, by means of an excellent automatic recording mechanism, that on June 23, 1885, the evaporation in 24 hours under a dry northwest wind was **four times as great** as upon another day in the same week when a moist wind was blowing from the south. See Appendix 2, page 426.

DIFFERENCES IN CONDITIONS

Conditions affecting evaporation from the Great Lakes are much out of line with those under which all available accurate data upon evaporation from other large reservoirs and lakes have been obtained, and very different from the conditions around the small experimental tanks from which formulas and constants for estimating evaporation have been worked up.

The areas of water surface of these lakes are so vast, and the distances across in direction of the wind, so great, that the problem of the invisible vapor blanket and the visible blanket of fog, as affecting diminution of evaporation, is different from that presented on the artificial reservoirs on which evaporation has been studied. The climate, and wind movement, and the amount of moisture in the air, which largely affects both radiation loss by night and absorption of heat from the sun, is vastly different over the Great Lakes, from that over the Salton Sea in southern California, or that at Reno, Nevada, or at Denver and Fort Collins, Colorado, where many of the experimental data of the past 20 years upon evaporation have been obtained.

The source and the rate of the supply of heat, or the thermal units, required to provide the quantity of heat that is rendered latent, or absorbed in the process of vaporization, has much to do with the depth or quantity of water evaporated in the course of an hour, or within a week or month.

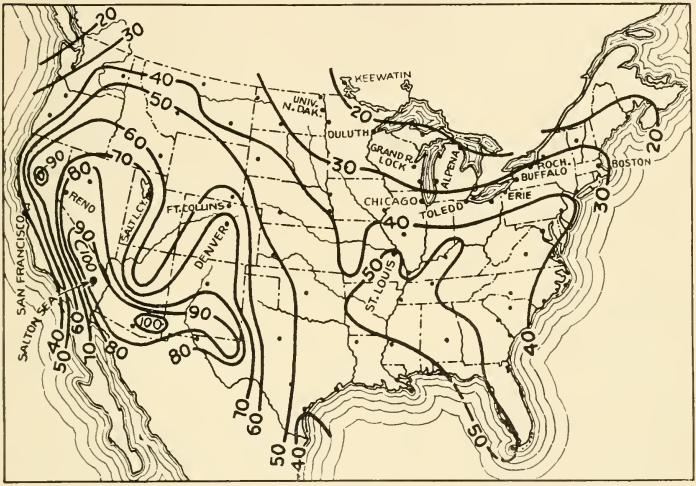
The abstraction of heat from the two films of water and air, at the surface of contact, chills them so as to greatly retard evaporation, unless the normal warmth of one or both of these surfaces is promptly restored, by convection, or other circulation of air, or water, or both; or from radiation.

The map on the next page may be accepted as showing with sufficient accuracy for present purposes the widely differing effects of the various conditions that control evaporation from reservoirs and small lakes in various parts of the United States.

It was **not prepared from actual measurements of evaporation** from reservoirs, but was estimated from data on temperatures of air and dew point, guided by daily measurements of evaporation for three months by Piché evaporimeters at 18 U. S. Weather Bureau stations, all observed within the thermometer shelters. The depth of evaporation per year was estimated by the same general methods for all parts of the country.

It is presented here for the purpose of showing the regions where similar climatic conditions affecting evaporation prevail, and where they differ. It indicates that the **data from observations near Boston, Rochester, and Wisconsin, and University of North Dakota, may be accepted for use in the Great Lakes region.**

In Colorado and California, conditions are so different in humidity, and in other respects, that data on the relation of temperature to evaporation in those regions must be used cautiously, if at all, for the present purpose of estimating the evaporation from these Great Lakes.



LINES OF EQUAL ANNUAL DEPTH OF EVAPORATION IN INCHES FROM A FREE WATER SURFACE

Computed from temperature, dew-point and a few records by Piché evaporimeters, at weather bureau stations from July, 1887, to June, 1888, by Prof. T. Russell

It is of interest to note that, without regard to the effect of wind or fog or the exceptionally cool water due to their depth, **the Great Lakes are within the zone of smallest evaporation in the United States.**

As one goes south the greater warmth increases evaporation; and west of the Mississippi basin the scant rainfall and the extreme dryness of the air also cause large evaporation.

DATA ON TEMPERATURE, HUMIDITY AND WIND

Accurate daily observations of maximum and minimum temperatures of the air, of rainfall, of wind movement, and of relative humidity, going back about half a century, are available at about 25 Weather Bureau stations, all excellently distributed around the shores of the Great Lakes. These were established by the Signal Service of the War Department, but for many years past have been managed by the Weather Bureau of the U. S. Department of Agriculture.

There have been **no systematic records of water temperatures in mid-lake regions, and but few observations of lake temperatures at stations near the shores,** and there are no records of dew-point temperatures, or of relative humidity, obtained in midlake. Nevertheless, sundry records have been found from which these have been determined approximately.

The source and quality of these data are discussed in Appendix No. 2.

From their earliest days these Weather Bureau stations have been supplied with excellent, calibrated instruments, in the hands of skilled observers, many of whom have been deeply interested in the growing science of meteorology, and some of whom have, from time to time, reported special studies containing data useful in the present problems.

The following tables and diagrams of isothermal lines were prepared from the records published year by year in the Monthly Weather Review of the U. S. Weather Bureau, by averaging the mean monthly values from 1900 to 1924, for all of the stations upon the Great Lakes; and making a slight adjustment to compensate for the observation stations being mostly on the south shores of the lakes, by means of the maps on page 86. Observations at Canadian Meteorological stations were included and given weight according to the larger area represented by each.

The vast number of observations, the locations on the opposite sides of each lake in the path of the wind, the humidity of which may be changed by contact with the waters of the lake, and the high quality of the meteorological service, **all present an extraordinarily good basis of facts** upon which to base logical deductions.

AVERAGE AIR TEMPERATURES AROUND GREAT LAKES FOR PAST 25 YEARS

	Lake Superior		Lake Michigan		Lake Huron		Lakes Erie and St. Clair		Lake Ontario	
Month	Average of Duluth Houghton Marquette Sault Ste. Marie A	Adopted Values * A-1.9	Average of Escanaba Green Bay Milwaukee Chicago Grand Haven Ludington B	Adopted Values * B-0.7	Average of Sault Ste. Marie Alpena Port Huron C	Adopted Values * C-0.5	Average of Detroit Toledo, Sandusky Cleveland Erie Buffalo D	Adopted Values * D-0.5	Average of Rochester Oswego E	Adopted Values * E-0.7
January	13.5	11.4	21.0	20.7	18.6	18.1	26.4	25.3	24.3	23.4
February	12.8	10.7	20.2	19.9	16.2	15.7	24.3	23.2	22.2	21.3
March	24.5	22.2	31.7	31.4	27.7	27.2	35.5	34.4	32.7	31.8
April	37.9	35.8	42.9	42.6	40.5	40.0	45.8	44.7	44.1	43.2
May	48.9	46.8	53.6	53.3	51.1	50.6	57.3	56.2	54.9	54.0
June	58.8	56.7	63.6	63.3	60.9	60.4	66.8	65.7	63.9	63.0
July	64.7	62.6	69.5	69.2	67.0	66.5	72.1	71.0	70.1	69.2
August	62.9	60.8	67.7	67.4	64.9	64.4	70.2	69.1	67.8	66.9
September	56.5	54.4	61.2	60.9	58.9	58.4	64.4	63.3	62.3	61.4
October	46.2	44.1	50.8	50.5	48.3	47.8	53.5	52.4	51.6	50.7
November	32.7	30.6	38.1	37.8	35.7	35.2	40.7	39.6	39.3	38.4
December	19.8	17.7	25.9	25.6	24.0	23.5	29.7	28.6	28.1	27.2
Mean Annual Temperature	39.9	37.8	45.5	45.2	42.7	42.2	48.8	47.8	46.8	45.9

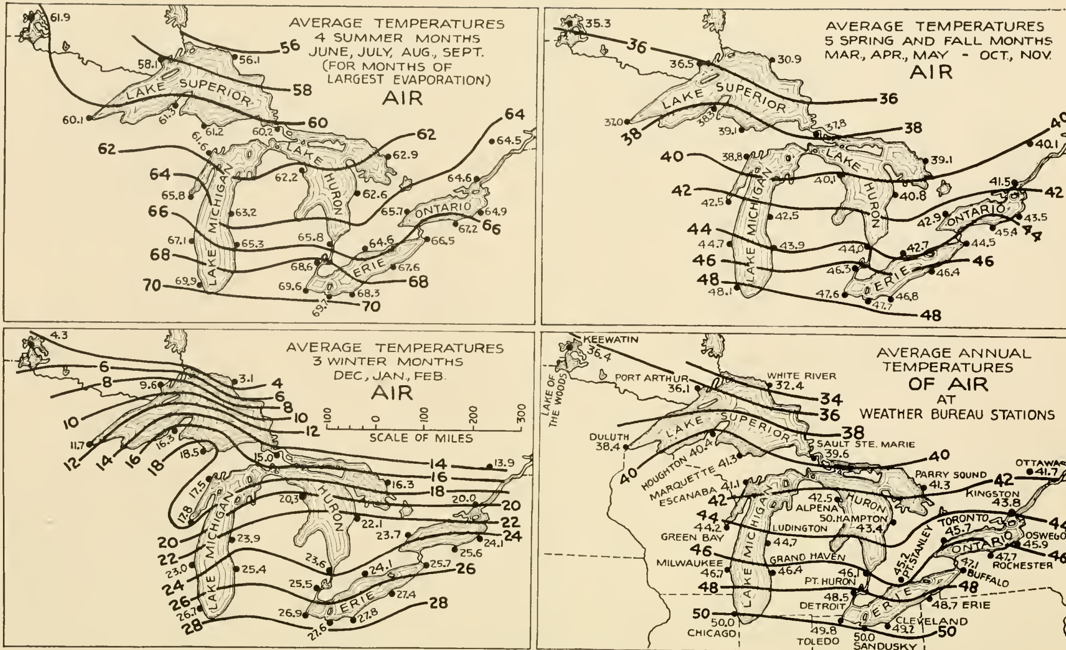
*These adjustments were based upon the relation of mean location of the observation stations to the location of the lake surfaces and the variation as shown by the isothermal lines in the maps which follow. Since the amount of evaporation is influenced more by the summer temperature than by the mean annual temperature, the isotherms for summer months were given greater weight in this adjustment.

From the above records, the following map of isotherms for air in different seasons of the year was prepared.

In general, air on the leeward side of a Great Lake will be a very few degrees warmer in winter than on the windward side, and in summer, when no strong winds are prevalent, by day there will be a gentle breeze from off the water onto the land, and a reversed breeze by night.

This frequent change in direction of wind shifts the effect of warming of the colder winter air, by contact or by radiation from the lake surface at 32° F., first to one side and then to the other of each lake; so that observations at these shore stations probably represent, very nearly, the average air temperatures, over the water, affecting evaporation.

In the more complete studies of the future, autographic temperature records of the air day by day, for a complete year, by delicate instruments maintained within standard "shelters" on car ferries crossing Lake Michigan, and on other boats traversing the lakes, would give valuable data.



ISOTHERMALS FOR GREAT LAKES REGION

BASED ON OBSERVATIONS BY U. S. WEATHER BUREAU (25 YEARS 1900 TO 1924 INCL.)
ALSO OBSERVATIONS BY CANADIAN WEATHER BUREAU (40 YEARS 1885 TO 1924 INCL.)

FOG OVER THE GREAT LAKES

The coolness of the lake water in proximity to the large amount of moisture put into the air by evaporation, causes a remarkably large amount of fog over the Great Lakes, **which has a great effect upon the evaporation.**

The standard of the Weather Bureau in counting foggy days, is that of a fog so dense that the visibility is not more than 1,000 feet. A distinction is made between fog and haze, the latter remaining to some extent after fog has evaporated, being caused by dust particles in the air.

The average percentage of foggy days in each calendar month for 10 years at various Weather Bureau stations around the Lakes, is given on the Meteorological Charts for the Great Lakes District, published in the years 1911–13, as per the following table, in which the localities are arranged with the most northwesterly at the top and proceeding toward the south and southeast for each lake. A figure is first given for the straight average for each group and below this, a weighted average figure, proportional to the area of lake adjacent to each station.

It will be seen that no one of the lakes is free from these fogs.

On the back of the chart for June 1911 is given another summary of fog conditions over the Great Lakes.

The following is abstracted from an article upon fogs over the Great Lakes, by H. C. Frankenfield, Professor of Meteorology at Washington, D. C., given in the book entitled "Weather Forecasting in the United States," published by the Government Printing Office in 1916:

Seasonal distribution of fogs is not well defined on Lake Superior and the northern part of Lake Michigan.

The northern portion of the Upper Lake region is much less subject to fog than the southern portion, the ratio being 1 to 6.

Professor Frankenfield notes the following five conditions as favorable for fog formation:

(1) On the Upper Lakes, fogs are usually preceded by low pressure on the leeward side of the lakes, and relatively high pressure on the windward side, with a weak pressure gradient, not greater than 0.10 inch per 100 miles, and usually less, perhaps averaging 0.10 inch to 250 miles. The gradient is usually least with southeast winds.

The height of barometer is not important for fog formation. In summer, the barometric pressure during fogs is usually low, because with high pressure the sharper temperature contrasts between water and land cause stronger winds, thereby preventing the formation of fogs.

(2) The second favorable condition, is that of more or less marked temperature differences between the water and land surfaces. **The water temperatures were lower in about two-thirds of the fog periods** without regard to the season of the year, although some general tendencies toward higher lake temperatures were noticed over the southwestern section during May and November.

PERCENTAGE OF DAYS IN EACH MONTH ON WHICH FOG WAS OBSERVED, DURING A PERIOD OF 10 YEARS, 1900-1909

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Aver-age
LAKE SUPERIOR													
Port Arthur, Ont	0	1	1	1	1	2	2	3	3	3	1	0	**1.5**
White River, Ont	0	1	1	1	0	0	0	1	1	1	1	0	**0.6**
Two Harbors, Minn	0	0	0	0	0	0	0	0	0	0	0	0	**0**
Eagle Harbor, Mich	1	1	2	2	13	22	19	10	6	2	3	1	**6.8**
Houghton, Mich	3	3	4	3	7	9	9	12	9	8	5	(4)	**6.3**
Duluth, Minn	4	6	9	9	22	23	16	16	17	12	8	7	**12.4**
Ashland, Wis	0	0	1	1	1	1	1	1	3	1	0	0	**0.8**
Marquette, Mich	3	1	4	5	14	16	11	7	9	3	1	1	**6.2**
Grand Marais Harbor, Mich	1	1	1	1	10	17	13	6	2	2	3	2	**4.9**
Whitefish Point, Mich	1	1	4	4	16	26	18	13	7	4	1	1	**8.0**
Sault Ste. Marie, Mich	8	10	7	3	3	4	4	7	10	9	5	2	**6.0**
Straight Average	**1.9**	**2.3**	**3.1**	**2.7**	**7.9**	**10.9**	**8.5**	**6.9**	**6.1**	**4.1**	**2.5**	**1.3**	**4.8**
Weighted Average	**1.2**	**1.6**	**2.2**	**2.0**	**5.4**	**7.7**	**6.1**	**5.1**	**4.3**	**3.0**	**1.9**	**1.0**	**3.5**
NORTHERN MICHIGAN													
St. James, Mich	—	—	0	0	0	0	0	0	0	0	0	0	**0**
Escanaba, Mich	7	12	14	12	12	9	7	8	16	10	8	4	**9.9**
Charlevoix, Mich	3	2	1	1	1	0	0	1	1	0	1	0	**0.9**
Menominee, Mich	1	1	1	1	3	1	1	0	0	0	0	1	**0.8**
Traverse City, Mich	2	1	1	1	1	0	1	0	1	0	0	1	**0.8**
Frankfort, Mich	1	1	2	1	3	5	2	0	2	2	2	0	**1.8**
Green Bay, Wis	6	4	4	3	2	2	3	3	5	4	4	6	**3.8**
Straight Average	**2.9**	**3.0**	**3.3**	**2.7**	**3.1**	**2.4**	**2.0**	**1.7**	**3.6**	**2.3**	**2.1**	**1.7**	**2.6**
Weighted Average	**2.5**	**3.1**	**3.7**	**3.0**	**3.7**	**1.9**	**2.2**	**1.8**	**4.0**	**2.7**	**2.4**	**1.4**	**2.7**
NORTHERN HURON													
Detour, Mich	0	4	7	2	9	5	7	6	6	5	4	2	**4.7**
Mackinac Island, Mich	4	1	2	4	5	6	4	2	8	1	2	4	**3.6**
Cheboygan, Mich	1	1	1	1	1	1	1	1	3	1	1	1	**1.2**
Parry Sound, Ont	1	1	0	1	1	1	1	1	1	1	1	0	**0.8**
Alpena, Mich	6	4	6	7	8	8	5	7	11	13	8	4	**7.2**
Straight Average	**2.4**	**2.2**	**3.2**	**3.0**	**4.8**	**4.2**	**3.6**	**3.4**	**5.8**	**4.2**	**3.2**	**2.2**	**3.5**
Weighted Average	**1.8**	**2.6**	**3.6**	**2.6**	**5.1**	**3.9**	**3.9**	**3.8**	**4.9**	**4.7**	**3.4**	**1.6**	**3.5**
SOUTHERN MICHIGAN													
Ludington, Mich	1	1	1	1	1	4	0	0	1	0	1	1	**1.0**
Sheboygan, Wis	1	2	1	1	0	1	0	0	2	1	1	0	**0.8**
Milwaukee, Wis	8	5	9	7	15	9	3	3	9	10	10	7	**7.9**
Grand Haven, Mich	7	9	12	9	12	8	6	8	15	13	8	7	**9.5**
South Haven, Mich	2	1	5	5	5	5	1	0	1	2	2	0	**2.4**
Chicago, Ill	13	11	12	14	9	8	7	5	5	7	9	11	**9.3**
Straight Average	**5.3**	**4.8**	**6.7**	**6.2**	**7.0**	**5.8**	**2.8**	**2.7**	**5.5**	**5.5**	**5.2**	**4.3**	**5.2**
Weighted Average	**5.9**	**5.3**	**7.2**	**6.6**	**7.8**	**6.3**	**3.1**	**3.0**	**6.1**	**6.1**	**5.8**	**5.0**	**5.7**
SOUTHERN HURON													
Saugeen, Ont	1	1	1	1	4	2	1	2	1	1	1	1	**1.4**
East Tawas, Mich	0	0	1	1	0	0	0	0	2	1	0	0	**0.4**
Port Austin, Mich	1	0	0	1	2	3	0	1	2	1	0	1	**1.0**
Bay City, Mich	1	0	0	0	0	0	0	0	0	0	0	1	**0.2**
Port Huron, Mich	11	7	12	11	6	12	3	10	14	12	12	10	**10.0**
Straight Average	**2.8**	**1.6**	**2.8**	**2.8**	**2.4**	**3.4**	**0.8**	**2.6**	**3.8**	**3.0**	**2.6**	**2.6**	**2.6**
Weighted Average	**2.8**	**1.7**	**2.7**	**2.8**	**3.3**	**4.0**	**1.0**	**3.0**	**3.8**	**3.0**	**2.7**	**2.7**	**2.8**
LAKE ERIE													
Port Stanley, Ont	6	5	5	5	6	4	2	20	7	7	6	3	**6.3**
Buffalo, N. Y	9	9	15	13	11	8	4	2	3	6	6	7	**7.8**
Detroit, Mich	9	4	7	5	5	4	2	6	5	11	9	11	**6.5**
Erie, Pa	5	4	6	3	2	2	3	22	3	1	1	3	**4.7**
Toledo, Ohio	7	7	7	3	3	2	1	2	8	7	10	10	**5.7**
Sandusky, Ohio	4	3	5	4	2	0	0	1	4	3	5	4	**2.9**
Cleveland, Ohio	4	7	12	6	5	5	6	2	6	3	5	5	**5.5**
Straight Average	**6.3**	**5.6**	**8.1**	**5.6**	**4.9**	**3.6**	**2.6**	**7.9**	**5.2**	**5.4**	**6.0**	**6.1**	**5.6**
Weighted Average	**5.9**	**5.4**	**7.8**	**5.5**	**4.8**	**3.5**	**2.6**	**9.8**	**5.2**	**4.9**	**5.4**	**5.1**	**5.5**
LAKE ONTARIO													
Toronto, Ont	2	2	2	1	1	1	1	1	2	2	2	1	**1.5**
Kingston, Ont	2	2	1	1	2	2	1	1	3	2	3	1	**1.8**
Cape Vincent, N. Y	0	0	0	0	0	0	0	0	0	0	1	0	**0.1**
Youngstown, N. Y	—	0	0	—	0	0	0	0	0	—	—	—	**0**
Oswego, N. Y	10	8	12	16	22	22	8	8	11	15	15	11	**13.2**
Straight Average	**2.8**	**2.4**	**3.0**	**3.6**	**5.0**	**5.0**	**2.0**	**2.0**	**3.2**	**3.8**	**4.2**	**2.6**	**3.3**
Weighted Average	**4.5**	**3.2**	**4.3**	**5.3**	**7.3**	**7.3**	**2.8**	**2.8**	**4.3**	**5.4**	**5.6**	**3.8**	**4.7**

(3) The third favorable condition, is **relative humidity above normal**, averaging above 90%; although lower in quite a fair percentage of the cases observed. Low humidity fogs are very local.

(4) The fourth condition favorable, is the occurrence of **precipitation from 24 to 36 hours previous to fog**, usually to the westward and southward of the lakes toward the LOWS. Precipitation in the LOWS generally continues while fogs prevail in the lake region, as the surface temperatures are higher and the moisture content is greater in the LOWS.

(5) The fifth condition is **low wind velocity** less than 15 miles per hour, and for about one-third of the time less than 6 miles. Fogs with wind above 15 miles an hour have their characteristics very well marked, and they occur usually in the spring and autumn, with the lake temperature almost invariably higher than air. However, during the winter fogs, with winds above 15 miles an hour, the lake temperatures are often the lower. There is a tendency for less fog over Lake Ontario, particularly over the eastern portion, than over Lake Erie.

MISCELLANEOUS OBSERVATIONS UPON FOG BY PROFESSOR FRANKENFIELD

(1) It is noticed that the belt of maximum fog frequently extends from about the southern third of Lake Michigan eastward to Lake St. Clair and extreme southern Lake Huron, and thence over western Lake Erie.

(2) A maximum of fog frequency occurs at Chicago, dense fogs often occurring at that place with none elsewhere along the lakes, doubtless due to excess of smoke. These fogs are usually shallow.

(3) Fogs usually occur in the form of a uniform cover, like a blanket; but frequently on Lake Superior they form in bands along shore and over the water.

Professor Frankenfield quotes from the Meteorological Chart of the Great Lakes for the season of 1899 (by Henry and Conger) as follows:

"It appears that fog does not generally appear in the blanket form, except when LOWS are moving slowly toward the lakes. The most frequent formation reported is the heavy banks, which are seen in their best form on Lake Superior. These banks appear frequently on the Great Lakes, with intervals of clear weather. Fog also appears in the belt or band formation, viz., a narrow band which extends for many miles in length.

"This formation is also most frequent on Lake Superior. One vessel will run for hours in the bank formation, while another vessel several miles distant, running parallel, will be in clear weather and can hear the fog whistle of the steamer in the fog, and also see the wall of the fog bank. These formations are most frequently reported during the summer months.

"It has been found that the approach of a LOW from the west of Lake Superior will cause fog to form over the western end of the lake. The fog appears to move eastward in the lifting conditions, so that as before stated, one steamer will make the run eastward on Lake Superior in fog, while one following, a few hours later, will not encounter anything, indicating that the fog banks move steadily eastward.

"Masters have reported that less fog was encountered after passing Sable Point, Lake Superior, on the Marquette, or Portage Entry, route than on the passage around Keweenaw Point. The reports appear to bear out this statement, in view of the fact that much less fog is reported from Marquette, or Portage Entry, and Houghton than from the Keweenaw Point route.

"The reports indicate that the most fog on Lake Superior is encountered between Whitefish Point and Keweenaw Point, and it is probable that vessel masters would encounter less fog by taking the Portage Entry course in preference to that around Keweenaw Point. This would probably be the case during the summer months, when fog is most frequently encountered on Superior."

METEOROLOGICAL CHARTS OF THE GREAT LAKES

The earliest of these Meteorological Charts, published by authority of the Secretary of Agriculture, under the direction of the Chief of the U. S. Weather Bureau, appear to have been the combined work of Professor Alfred J. Henry, and Mr. Norman B. Conger during the years 1899 to 1907, and charts for each month for the years 1911, 1912, 1913 have been examined for the purposes of these studies. They contain a great variety of information useful to shipmasters, and others, about average conditions of wind and weather to be expected, the tracts of storms, the relative intensity and force of wind from each of the 8 points of the compass, and the general trend of surface currents within the lakes.

The data upon these charts which have a particular bearing upon evaporation are:

(1) The "Wind Rose," which shows that, in general, winds from the west have a predominance, although there is an important wind motion from each direction, at each of the 50 observation stations. These diagrams, showing the prevailing force and direction of winds, indicate that the data concerning temperature, dew-point and wind effect, at the several Weather Bureau stations which have been used in compiling data for estimating evaporation from the lake surface, are fairly representative of conditions all over the lakes.

FOG ZONES OVER THE LAKES

(2) These charts show, month by month, during the navigation season, from May to November inclusive, the relative percentage of days of fog over each lake, by means of a blue over-print in three shades, showing respectively the localities where there were from 1 to 10%, from 10 to 25%, from 40 to 45% of days with fog, during that particular month.

The 30 monthly sheets examined, indicated much irregularity, with June, July and August showing the zones containing the largest number of foggy days. The extent of the fog zones are not shown on the charts for December, January and February, probably because of lack of information from shipmasters, and thus the relative number of foggy days, as summarized by Professor Frankenfield, cannot be checked up on these charts.

The charts show large areas of lakes with from 10 to 25% of fog in September and October, but the November charts make it plain that the percentage of foggy days, and the area of the fog zones, decrease with the advent of colder weather; so that on all of the lakes, during November, there are generally only from 1% to 10% of foggy days. The chart for November 1911 mentions that at this time of year the temperature of water and air are normally about equal.

The fog data on these charts seem at times at variance with the tables and conclusions presented by Prof. Frankenfield given on the previous pages possibly because of the observers having been mainly afloat in one case and ashore in the other.

The instruments at the Weather Bureau Stations tell only a part of the story. More data should be sought in the future through the cooperation of shipmasters.

(3) These charts show the average thickness of ice found in the prominent lake harbors, as an average for each month of weekly measurements, for a 11-year period—1900 to 1910—as by the following table.

The figures given in the table below are taken from the Meteorological Charts of the Great Lakes, published by the U.S. Weather Bureau, 1911 to 1913. Ice commonly increases in thickness, more or less, until the warmth of spring "rots" it or changes its crystaline structure. Presumably the thickness found in these harbors is greater than would be found at more exposed locations around the borders of the lakes.

Average Thickness of Ice (Inches Depth) in Harbors around the Great Lakes, during November, December, January, February and March, for the twelve years, 1900 to 1911 inclusive.

Lake and Harbor	Month	1900	1901	1902	1903	1904	1905	1906	1907	1908	1909	1910	1911	Av'ge
LAKE SUPERIOR														
Duluth, Minn.	Nov.	3.6	3.0	0.5	4.9	2.0	2.0	**	**	0.0	**	5.0	7.0	2.3
	Dec.	10.2	8.8	7.9	16.3	9.2	8.1	9.2	4.9	9.8	8 3	7.6	9.6	9.2
	Jan.	12.0	20 0	14.6	18.8	26.5	15.9	17.2	21.8	13.6	17.8	22.0	21.8	18.5
	Feb.	23.8	23.7	22.5	27.9	34.4	27.9	22.9	29.8	20.8	23.6	29.3	30.8	26.4
	Mar.	27.6	24.4	19.2	29.1	38.0	23.5	17.4	23.0	18.9	17.7	31.6	27.0	24.8
Houghton, Mich.	Nov.	....	....	....	....	....	....	....	....	....	....	....	0.0	....
	Dec.	6.3	4.3	6.8	6.2	4.5	5.0	5.3	3.6	5.9	3.5	3.9	2.6	4.8
	Jan.	....	10.3	13.6	14.3	11.6	13.0	14.5	13.5	10.4	10.3	8.2	11.9	12 0
	Feb.	*	18.3	16.3	17.0	20.0	18.0	18.2	17.0	15.8	12.9	12.7	12.9	16.3
	Mar.	....	20.3	10.5	10.0	24.0	21.6	20.5	18.0	18.9	14.0	12.4	10.5	16.4
Marquette, Mich.	Nov.	....	....	....	....	....	....	....	....	....	....	....	0.0	....
(Note warm loop in isothermal diagram, page 86)	Dec.	0 0	0.3	0.0	0.8	**	0.1	0.0	*	0.0	0.0	0.0	0.0	0.1
	Jan.	0.2	0.4	0.1	1.4	4.9	1.1	0.5	2.5	0.8	1.1	‡	‡	1.4
	Feb.	5.2	3.1	11.5	6.1	17.1	11.8	0.5	6.6	1.5	4.6	12.0	5.2	7.1
	Mar.	13.7	10.3	0.0	0.0	24.7	12.8	4.8	8.4	7.1	8.5	‡	‡	9.0
Sault Ste. Marie, Mich.	Nov.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0 0
	Dec.	4.5	3.5	0.0	11.0	5.5	*	3.8	0 0	*	1.2	4.2	1.0	2.9
	Jan.	11.2	12.8	12.9	13.2	16.0	13.4	5.9	10.9	7.1	6.0	10.2	10.9	10.9
	Feb.	18.9	18.5	20.5	17.5	25.4	21.5	16.0	20.2	16.0	15.0	14.6	18.4	18.5
	Mar.	22.8	21.0	13.0	17.7	27.0	24.0	16.0	20.2	17.0	19.0	15.0	21.6	19.5
LAKE MICHIGAN														
Escanaba, Mich.	Nov.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Dec.	0.0	4.5	5.5	14.0	10.0	2.0	4.0	*	3.0	2.0	2.0	**	4.3
	Jan.	6.1	9.2	13.0	10.4	20.5	14.2	6.6	13.0	5.0	12.5	13.5	11.7	11.3
	Feb.	21.6	18.2	22.6	19.0	29.3	20.8	16.6	24.2	19.0	20.5	22.5	17.6	21.0
	Mar.	27.0	23.2	17.2	20.1	31.1	22.9	22.9	22.7	22.2	21.7	20.1	18.4	22 5
Green Bay, Wis.	Nov.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(Note inland, sheltered location)	Dec.	3.5	7.0	4.0	5.8	6.4	3.2	4.8	3.8	4.5	6.0	4.4	4.0	4 8
	Jan.	6.0	10.4	12.8	6.9	15.0	9.0	6.9	7.1	6.5	9.0	11.8	7.3	9.1
	Feb.	12.0	15.9	13.2	7.7	21.0	17.2	11.1	12.1	11.8	9.0	14.0	7.0	12 7
	Mar.	9.3	14.1	4 0	14.0	20.0	6.3	4.5	8.0	12.0	7.0	6.5	4.0	9.1
Milwaukee, Wis.	Nov.	....	....	....	....	....	....	....	....	....	....	....	....	....
(Little ice south of these latitudes)	Dec.	0.0	0.8	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**	0.2
	Jan.	....	....	....	....	....	....	....	....	....	....	....	....	....
	Feb.	0.5	0.5	0.5	0.0	0.0	7.5	0 0	0.0	0.0	0 0	0 0	0.0	0 8
	Mar.	3.1	0.0	0.0	0.0	0.0	0.0	0 0	0.0	0.0	0.0	0 0	0 0	0.3
Grand Haven, Mich.	Nov.	0.0	0.0	0.0	....	....	....	0.0	0.0	0.0	0.0	0.0	0.0	0 0
	Dec.	0.0	0.0	0.0	....	....	....	0.0	0.0	0.0	0.0	0.0	....	0 0
	Jan.	....	....	....	*	*	*	....	....	....	....	....	....	....
	Feb.	1.8	1.4	8.8	1.0	*	*	0.2	0.0	0.5	0.0	0.0	0.0	1 4
	Mar.	0.8	0.2	0.0	*	*	*	0.0	0.0	0.0	0.0	†	0	0.1
Chicago, Ill.	Nov.	....	....	....	....	....	....	....	....	....	....	....	....	....
	Dec.	....	....	....	....	....	....	....	....	....	....	....	....	....
	Jan.	....	....	....	....	....	....	....	....	....	....	....	....	....
	Feb.	....	....	....	....	....	....	....	....	....	....	....	....	....
	Mar.	....	....	....	....	....	....	....	....	....	....	....	....	....

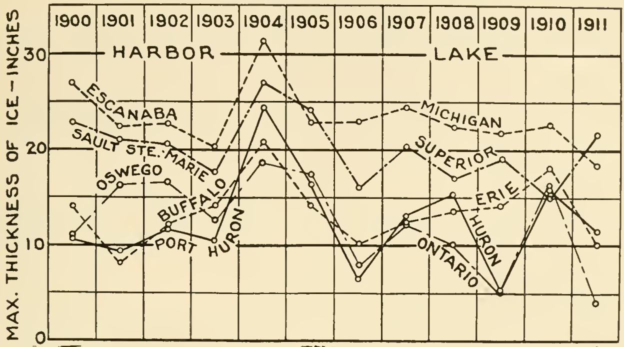
Average Thickness of Ice (Inches Depth) in Harbors Around the Great Lakes. (Continued.)

Lake and Harbor	Month	1900	1901	1902	1903	1904	1905	1906	1907	1908	1909	1910	1911	Av'ge
LAKE HURON														
Alpena, Mich.	Nov.	....	....	....	....	....	....	....	....	....	....	....	**	....
	Dec.	2.5	4.5	2.0	5.0	1.5	1.5	8.0	1.5	0.2	3.0	3.5	1.0	**2.8**
	Jan.	0.5	5.5	3.8	9.0	11.1	10.8	7.6	2.4	0.1	2.2	4.6	8.6	**5.5**
	Feb.	4.0	7.2	13.4	13.0	22.1	17.8	17.8	14.1	4.5	5.0	5.0	7.1	**10.9**
	Mar.	6.4	5.6	4.8	4.0	28.0	16.0	9.2	14.2	6.2	4.6	**	10.7	**9.2**
Port Huron, Mich.	Nov.	....	....	....	*	*	....	....	....	....	....	....	**	*
	Dec.	1.0	5.1	2.8	9.1	3.8	1.8	3.6	2.6	0.2	4.3	2.4	**	**3.1**
	Jan.	5.7	6.0	8.5	10.4	17.1	10.3	3.2	2.2	8.8	2.8	13.3	11.6	**8.2**
	Feb.	7.9	9.2	11.8	7.6	24.4	16.2	6.4	13.0	15.1	5.2	15.8	8.8	**11.8**
	Mar.	10.5	5.6	2.0	1.3	15.2	11.0	4.9	6.8	10.0	2.2	0.0	2.5	**6.0**
LAKE ERIE														
Detroit, Mich.	Nov.	....	....	....	....	....	....	....	....	....	....	....	0.0	....
	Dec.	1.6	4.0	5.5	7.2	4.0	0.0	0.2	0.8	1.2	4.2	4.1	†	**2.7**
	Jan.	....	....	....	....	....	....	....	....	....	....	....	....	....
	Feb.	9.4	9.8	14.6	6.8	23.6	18.8	7.0	9.8	12.0	4.8	10.2	6.5	**11.1**
	Mar.	....	....	....	....	....	....	....	....	....	....	....	....	....
Toledo, Ohio	Nov.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
	Dec.	0.5	4.8	1.0	6.0	3.1	0.6	0.3	0.0	0.1	5.8	5.0	**	**2.3**
	Jan.	5.4	3.0	4.0	6.2	10.0	6.5	1.5	0.5	3.5	3.0	10.2	6 2	**5.0**
	Feb.	5.9	9.5	6.9	4.0	9.6	11.6	5.6	9.0	9.0	1.8	12.1	†	**7.7**
	Mar.	5.0	4.0	0.0	0.0	4.5	4.5	0.6	5.5	†	0.0	0 0	0.0	**2.2**
Sandusky, Ohio	Nov.	0.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	....	**	**0.2**
	Dec.	†	8.0	6.5	11.0	7.0	3.0	4.5	4.0	3.0	8 5	10.0	**	**5.5**
	Jan.	6.5	3.7	10.8	10.2	14.0	8.4	2.5	3.3	4.5	3 3	11.8	9.5	**7.7**
	Feb.	6.5	9.9	15.2	7.2	18.4	18.2	7.8	9.0	10.9	2.5	18.2	4.8	**10.7**
	Mar.	4.8	6.4	0.0	3.0	3.5	10.5	2.6	2.5	2.8	0.4	†	0.0	**3.3**
Cleveland, Ohio	Nov.	....	....	....	....	....	....	....	....	....	....	....	0.0	....
	Dec.	0.0	1.3	0.0	1.5	0.0	0.0	0.0	0.0	0.0	1.2	2.0	**	**0.5**
	Jan.	5.0	2.5	3.2	4.0	8.2	7.2	0.0	3.8	†	3.5	15.3	6.0	**5.3**
	Feb.	5.6	11.2	7.5	3.4	15.2	15.0	4.5	10.2	6.2	1.0	16.4	†	**8.7**
	Mar.	3.2	3.0	2.5	0.7	5.5	9.8	0.8	3.8	1.8	0.0	5.0	†	**3.3**
Erie, Pa.	Nov.	....	....	....	....	....	....	....	....	....	....	....	0.0	....
	Dec.	0.1	1.7	1.4	3.0	3.5	....	0.4	....	....	4.5	4.5	0.0	**2.1**
	Jan.	2.0	2.5	6.7	7.8	12.5	9.7	0.8	1.4	3.2	1.4	10.5	5.0	**5.3**
	Feb.	6.0	12.0	15.4	5.0	14.6	18.0	4.9	9.5	8.4	1.0	13.6	0.8	**9.1**
	Mar.	....	9.0	2.4	0.5	5.4	12.9	3.6	6.6	3.0	0.8	3.2	0.4	**4.3**
Buffalo, N. Y.	Nov.	....	....	....	....	....	....	....	....	....	....	....	0.0	....
(Buffalo harbor is commonly	Dec.	0.0	2.0	1.0	7.0	2 0	0.0	1.0	1.0	0.0	3.0	5.0	0.0	**1.8**
ice bound for one or two	Jan.	10.0	5.0	7.0	8.0	14.5	12.0	1.0	8.0	7.0	1.5	10.5	10.0	**7.9**
weeks later than Cleveland)	Feb.	14.0	8.0	12.0	14.0	20.5	14.0	10.0	11.0	13.5	6.0	18.0	10.0	**12.6**
	Mar.	10.0	6.0	8.0	12.0	20.0	13.0	7.0	12.5	11.0	14.0	14.0	6.0	**11.5**
LAKE ONTARIO														
Oswego, N. Y.	Nov.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
	Dec.	2.2	2.2	1.5	2.2	6.1	1.0	4.5	0.2	0.4	2.0	1.8	0.0	**2.0**
	Jan.	5.4	8.0	8.9	8.0	13.4	13.0	1.6	1.4	2.2	4.6	9.0	3.1	**6.6**
	Feb.	6.2	16.2	16.5	12.5	18.3	17.1	7.7	11.9	10.0	5.0	15.9	4.0	**11.8**
	Mar.	11.0	15.2	6.7	4.0	15.4	12.9	0.9	12.1	5.8	0.7	2.0	1.0	**7.3**
Rochester, N. Y.	Nov.	....	....	....	....	....	....	....	....	....	....	....	0.0	....
	Dec.	0.5	0.0	1.6	6.8	3.5	0.5	1.0	0.0	0.0	1.6	3.2	0.0	**1.6**
	Jan.	....	....	....	....	....	....	....	....	....	....	....	....	....
	Feb.	2.5	12.1	12.4	1.6	7.0	13.0	3.9	8.0	4.0	18.8	5.2	1.0	**7.5**
	Mar.	3.9	8.2	0.0	0.0	0.0	7.6	0.6	5.2	0.1	0.0	0.0	0.0	**2.2**

* Data Missing. † Floating Ice. ‡ Shore Ice. ** Indicates trace.

Little ice of importance to navigation forms south of the latitude of Milwaukee and Grand Haven; and the southern portion of Lake Michigan is seldom closed to navigation.

The following diagram showing annual variations is made up from figures for maximum thickness given in the preceding table.



MAXIMUM MONTHLY AVERAGE THICKNESS OF ICE IN EACH YEAR AT HARBOR NEAREST OUTLET OF EACH GREAT LAKE

1901 and 1918 gave the worst ice-jams restricting discharge in St. Clair River of which record is at hand

It was thought, at first, that this maximum thickness in the different years might give some indication as to the years in which the greatest obstruction of discharge of the lakes would be found, particularly in the St. Clair and Niagara Rivers, but apparently the ice gorges that obstruct discharge depend largely upon other factors than maximum thickness.

A somewhat similar study of the temperature records, at Weather Bureau stations around the lakes, failed to establish any definite relation between low temperatures and amount of obstruction of discharge by ice.

So far as the writer could learn, the two winters 1901 and 1918 presented abnormally large obstruction to outflow by ice, but in the diagram above, 1901 shows much less thickness of ice than 1904.

The ice-gorge, and the obstruction to flow, apparently, may be caused by ice of moderate thickness, perhaps from 6 inches to 1 foot, such as may be readily broken and detached from its anchorage to the shore, and thrown into the current at the outlet of the lakes by wind.

No data are available as to the proportion of the entire lake surface covered with ice in different winters.

On the chart for November 1911 it is noted that in Lake Superior during the 11 years—1900 to 1910—the thickness of the ice was greatest in 1910 and least in 1908.

On the chart for January 1912, it is noted that the greatest thickness of ice during the period from 1900 to 1911 occurred in 1904. This chart also records that during December 1911, outside of the harbors, floating ice fields extended about one mile from shore, and on Lake Superior, by the end of January, extended beyond vision; only a little open water being visible.

In 1904, in the upper part of Lake Michigan, ice fields were of an unusual extent, and in the lower part of the lake, which is usually open during the entire year, navigation was interrupted. In the western end of Lake Erie teams crossed between Kelly's Island and Bass Island during January 1904, and the eastern end of Lake Erie was covered with ice, from shore to shore.

In Lake Ontario there were large ice fields, and no water in sight from shore during the last half of the month of January, 1904.

Concurrent notes are given on other charts, all to the effect that the greatest thickness of ice during the period of 13 years from 1900 to 1912, occurred in 1904.

The fact that no open water was visible from the shore, tells very little about the percentage of total lake surface that was covered with ice, because of the three larger lakes having an average width of from 50 to 150 miles, **there might be open water over more than 75% of the entire surface, without any open water being visible from shore.**

There is a natural tendency to over-estimate the proportion of ice-cover. The only hope of accurate data upon per cent of ice-cover seems to lie in a few air plane flights made each year for this special purpose.

Dates of Opening and Closing of Navigation on the Great Lakes

(From War Department Navigation Charts)

LOCATION	AVERAGE DATES		Years Used for Averages	Average No. of Days Closed
	Opening	Closing		
LAKE SUPERIOR				
Duluth, Minn.	Apr. 22	Dec. 15	48	127
Marquette, Mich.	May 3	Nov. 28	25	156
Port Arthur, Ont.	May 1	Dec. 21	23	131
Sault Ste. Marie, Mich.	Apr. 25	Dec. 3	42	143
LAKE MICHIGAN				
Straits of Mackinac, Mich.	Apr. 12	Dec. 15	19	115
Escanaba, Mich.	Apr. 20	Dec. 6	25	135
Milwaukee, Wis.	Mar. 10	Feb. 24	24	14
Grand Haven, Mich.	Feb. 18	Feb. 4	28	14
Chicago and Calumet Rivers	Feb. 27	Jan. 7	25	51
LAKE HURON				
Alpena, Mich.	Apr. 6	Dec. 19	18	108
Detour Passage	Apr. 13	Dec. 9	22	125
Harbor Beach, Mich.	Apr. 3	Dec. 20	17	104
Owen Sound, Ont.	Apr. 19	Dec. 6	29	134
Port Huron, Mich.	Apr. 4	Dec. 11	25	114
LAKE ST. CLAIR				
Wind Mill Pt.	Apr. 2	Dec. 21	22	102
St. Clair Flats Canal	Apr. 4	Dec. 15	22	110
LAKE ERIE				
Detroit, Mich.	....	....	....	.....
Buffalo, N. Y.	Apr. 12	Dec. 19	11	115
Erie Canal	May 2	Dec. 3	11	151
Welland Canal	Apr. 17	Dec. 10	53	128
Erie, Pa.	Apr. 8	Dec. 21	23	108
Port Stanley, Ont.	Mar. 30	Dec. 18	29	102
Cleveland, Ohio	Mar. 23	Dec. 20	29	93
Toledo, Ohio	Apr. 1	Dec. 10	25	112
LAKE ONTARIO				
Cape Vincent, N. Y.	Apr. 10	Dec. 20	20	111
Kingston, Ont.	Apr. 8	Jan. 2	64	96
Oswego, N. Y.	Apr. 4	Dec. 17	36	108
Rideau Canal, Kingston	May 1	Nov. 28	48	154

This table giving average dates of the opening and closing of navigation at harbors around the Great Lakes, was prepared from information given on the navigation charts issued by the War Department of the U. S. Government, in order to show the approximate time that ice is found at different locations around the lakes.

These harbors, also the bays, become closed by ice long before the ice-cover extends very far into the broad, unsheltered, deeper waters of the lake.

EVAPORATION ESTIMATED BY FOUR DIFFERENT METHODS

Because of the importance of bringing plainly into view the difficulties and **uncertainties which come in applying ordinary methods** to estimating the evaporation from the Great Lakes, from the temperature of the air and the wind velocities recorded at adjacent Weather Bureau stations. The evaporation from each lake has been worked out in **four different ways in the present report, from meteorological data,** in addition to the hydrographic study, by difference between inflow and outflow, on previous pages.

(1) By the estimates by Professor Thomas Russell, in 1888, from a year's records of air temperature (wet and dry-bulb) and dew-point temperatures observed in the thermometer shelters of Weather Bureau stations on the shores of the Great Lakes, aided by three months observations with Piché evaporimeters.

These estimates for conditions on shore, are presented for comparison with the results of more recent methods, although they take no special account of the abnormal conditions of larger force of wind, coolness of water and absence of ice cover over the lakes.

This method takes account of humidity, and should give accurate comparative results in regions where wind averages about the same, and for shallow lakes or reservoirs in which the surface of the water or ice takes on substantially the same temperature as the air.

(2) By the ordinary method, from **the mean temperature of the air** in each calendar month, and the record of mean depth evaporated at the data stations under this same mean temperature of the air during that calendar month.

This method omits taking special account of any differences in water temperature, humidity and wind. In other words, it assumes these conditions are the same over the lakes as at the data stations.

The reason for this being the ordinary method is that the temperature of the air is conveniently available from the published records of the U. S. Weather Bureau, whereas, accurate records of water temperature are seldom available.

The surface water temperature of the Great Lakes—not covered by ice in winter—plainly, presents a condition very different from that of ordinary reservoirs.

(3) By a method similar in all respects to the second method, except that the **mean temperature of the water,** at the surface of the lake or reservoir, is used as the basis of computation.

(4) By **applying the physical laws that control evaporation** (so far as these are known), an attempt has been made to include compensation and adjustment for these differences in temperature, for vapor-pressure differences, and for wind effect, found over the Great Lakes.

This fourth method starts with the same data that were used in the first three methods, in inches depth per month evaporated at the data stations, in Boston, Rochester, etc., under stated mean monthly temperatures, humidities and wind velocities.

It is very remarkable that no other data can be found recorded, that include the necessary factors of water temperature, dew-point temperature and wind movement, measured under climatic conditions substantially the same as those over the Great Lakes, besides those at Boston, Rochester, University of N. Dakota, and Grand River Lock, Wisconsin.

None of the results by these four methods presents as high a degree of certainty and precision as is desirable. The data on water and dew-point temperatures at mid-lake, for the fourth method, are somewhat uncertain, but the differences in the four sets of results, derived from the most careful use of the best data that are now available, at least reveals the lack of data, and the lack of precision found by methods commonly used for estimating evaporation, when applied to this case.

We can have confidence, that for the lakes as a whole, the evaporation certainly averages more than two feet per year, and certainly less than three feet; and is probably about 22 inches on Superior, 27.5 inches on Michigan-Huron, 36 inches on Erie, and 33 inches on Ontario; and **about 27 inches, or say two and a quarter feet, for the 5 Great Lakes as a whole.**

The results found by the fourth method are confirmed, in a remarkable way, by the studies of difference between inflow and outflow for each lake, described in the preceding pages.

The probabilities are that the monthly values for each lake, found by making a weighted average of the results of the fourth method and the hydrographic method, are each within a half inch of the truth.

The first necessary step toward a higher degree of precision, should be systematic observations of evaporation, for from 1 year to 5 years, on large floating tanks, two on opposite sides of each lake. Tanks on a rigid base, on piers or islands, would serve equally well, or better than floating tanks; if the water in them is kept carefully at lake temperature, and slightly agitated and warmed in extremely cold weather, barely enough to keep, say, 98 per cent of the surface free of a sheet of ice, but not warmer than 32° F.

FIRST METHOD

Estimate of Evaporation Based on Temperature of Wet-Bulb Thermometer and Dew-Point, with Aid of Piché Evaporimeter

An independent line of evidence on evaporation on shore around the Great Lakes, was found in the estimates made by Professor Russell for May 31 to September 30, 1888, for conditions within the Weather Bureau shelters, **from tri-daily observations of wet-bulb temperature and dew-point,** at each of the main weather bureau stations about the lakes, based on three month's observations by Piché evaporimeters at some of the stations, and controlled by comparison with the Boston Fitzgerald experiments.

The only observations by the Piché evaporimeter made anywhere around the Great Lakes, were those maintained at Buffalo and Chicago.

The Piché instrument has since been somewhat discredited as an instrument of precision for estimating evaporation from open water surfaces, and is no longer used by the U. S. Weather Bureau in station equipment. It is a useful instrument for some purposes, but its presentation of evaporating surface to the air is more analogous to that presented in transpiration from the surface of a leaf or other vegetation, than to a reservoir surface. The indications of the form of Piché instrument heretofore used, are not directly applicable to estimating with precision the evaporation to be expected from a large water surface in the open air. (The writer believes a more accurate form could be devised.)

In these studies, Professor Russell deducted 25% from the indications of his Piché instrument. The results of Professor Russell's revised estimates are given in the table on the following page and in the diagram on page 100.

These values are copied from an article, "Depth of Evaporation in the United States" by T. Russell, Assistant Professor, Signal Corps, in the *Monthly Weather Review*, September, 1888, and form a part of the study referred to on page 96.

A monthly average of Professor Russell's estimates for each lake has been added by the present writer.

Depth of Evaporation in inches, in thermometer shelters at Signal Service Stations, near shores of Great Lakes

Computed from means of the Tri-daily Determination of Dew-Point and Wet-Bulb Temperatures

Stations	Jan. 1888	Feb. 1888	Mar. 1888	Apr. 1888	May 1888	June 1888	July 1887	Aug. 1887	Sept. 1887	Oct. 1887	Nov. 1887	Dec. 1887	Year
Lake Superior													
Duluth	0.5	0.5	0.6	1.5	2.4	2.5	3.9	3.4	3.0	2.5	1.2	1.0	**23.0**
Marquette	0.8	0.8	0.9	1.7	2.4	3.3	3.4	3.3	3.1	2.2	1.3	1.3	**24.5**
Average	**0.65**	**0.65**	**0.75**	**1.6**	**2.4**	**2.9**	**3.65**	**3.35**	**3.05**	**2.35**	**1.25**	**1.15**	**23.75**
Lake Huron													
Alpena	0.7	0.6	0.9	1.6	2.1	3.6	3.8	3.7	2.8	2.2	1.5	0.8	**24.3**
Port Huron	0.6	1.0	1.1	2.6	3.0	3.8	4.6	4.2	3.2	2.5	1.7	1.0	**29.3**
Average	**0.65**	**0.8**	**1.0**	**2.1**	**2.55**	**3.7**	**4.2**	**3.95**	**3.0**	**2.35**	**1.6**	**0.9**	**26.8**
Lake Michigan													
Green Bay	0.5	0.6	0.8	1.7	2.5	4.1	5.6	4.2	3.0	2.4	1.9	0.9	**28.2**
Milwaukee	0.5	1.0	1.1	2.4	2.6	3.8	4.8	3.7	3.4	2.9	1.9	0.9	**29.0**
Chicago	1.0	1.2	1.8	3.0	3.3	4.8	5.4	5.3	4.1	3.2	2.3	1.2	**36.8**
Grand Haven	0.5	0.7	1.3	2.6	3.1	3.8	4.7	3.8	2.7	2.6	1.7	1.1	**28.6**
Average	**0.62**	**0.87**	**1.25**	**2.42**	**2.87**	**4.12**	**5.12**	**4.25**	**3.3**	**2.8**	**1.95**	**1.02**	**30.65**
Lake Erie													
Detroit	0.8	1.1	1.6	3.0	4.1	4.8	5.9	5.2	3.4	2.8	2.0	1.3	**36.0**
Toledo	0.9	1.1	1.5	3.5	3.8	4.6	6.0	6.4	3.7	3.4	2.4	1.3	**38.6**
Sandusky	0.8	1.4	1.5	3.2	3.7	4.6	5.4	5.4	3.7	3.4	2.4	1.3	**36.6**
Cleveland	1.1	1.4	1.5	2.9	3.3	4.4	5.2	4.9	3.8	3.4	2.4	1.4	**35.7**
Erie	1.0	1.4	1.4	2.7	3.7	4.6	5.5	4.8	3.1	2.5	1.9	1.2	**33.8**
Buffalo	0.8	1.1	1.3	2.2	3.3	3.9	4.9	5.2	3.9	2.8	1.9	1.6	**32.9**
Average	**0.9**	**1.25**	**1.46**	**2.91**	**3.65**	**4.48**	**5.48**	**5.31**	**3.6**	**3.05**	**2.16**	**1.35**	**35.6**
Lake Ontario													
Oswego	0.6	1.0	1.1	2.2	2.8	3.8	3.9	4.0	3.6	2.7	2.2	1.0	**28.9**
Rochester	0.5	1.1	0.9	2.6	3.8	4.9	4.6	4.1	3.8	2.6	2.2	1.3	**32.4**
Average	**0.55**	**1.05**	**1.0**	**2.4**	**3.3**	**4.35**	**4.25**	**4.05**	**3.7**	**2.65**	**2.2**	**1.15**	**30.65**

The above values were computed by the following special formula by Professor Russell.

$$E = \frac{30[A p_w + B(p_w - p_d)]}{b}$$

in which

E is the evaporation in inches depth per month;

p_w is the vapor tension corresponding to the monthly mean of the wet-bulb temperature;

pd is the vapor tension corresponding to the monthly mean dew-point temperature;

b is the mean barometer reading;

A is a constant equal to 1.96; and

B a constant equal to 43.9.

The quantities obtained from the above formula have been multiplied by a factor 1.03 for months of 31 days, and divided by 1.03 for February.

This formula contains no variable factor, for variation in wind.

The values thus obtained represent **evaporation inside of the shelters** when the velocity of the wind outside is 7.1 miles per hour, which was the mean of the velocities at the stations where the Pichés were observed while this formula was being developed, during June 1888.

This 7.1 miles outside, is said to probably correspond to a velocity of **3.5 miles per hour inside the shelter.**

The Barometer Factor indicates that at an altitude 5,000 feet higher than that of the Great Lakes above sea level, one should expect an evaporation $\frac{30.00}{24.79} = 1.21$ or 21 per cent greater.

Professor Russell notes that the wet-bulb temperature is **practically that of a surface film from which water is evaporating.**

The only actual observations with Piché instruments on the shores of the Great Lakes appear to have been the following:

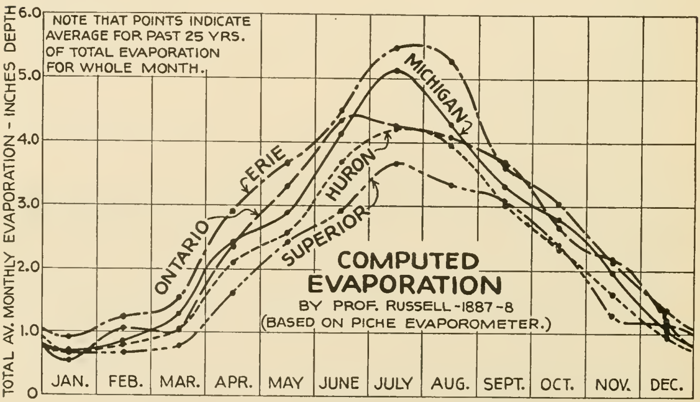
The total depth of evaporation each month shown by the Piché instrument and the mean wind velocity for that month as published by the Weather Bureau are given in the following table.

Station	June, 1888		July, 1888		August, 1888		Sept., 1888	
	Inches Depth of Evap. Obsd.	Average Wind Velocity M. P. H.	Inches Depth of Evap. Obsd.	Average Wind Velocity M. P. H.	Inches Depth of Evap. Obsd.	Average Wind Velocity M. P. H.	Inches Depth of Evap. Obsd.	Average Wind Velocity M. P. H.
Buffalo	..	..	..	..	..	..	3.70	8.1
Chicago	5.59	10.3	5.52	8.7	6.97	10.4	5.79	9.3

The fact that so few Piché observations were made around the Great Lakes illustrates the large extent to which the values for Russell's mean monthly totals of evaporation for all parts of the United States are based upon the ordinary routine tri-daily observations of the standard Weather Bureau station, and the small extent to which the Piché instrument was used as a guide; otherwise than in establishing his formula.

That the difference between the temperature of the wet-bulb and that of the dew-point is sometimes so very small as to give an uncertain base from which to estimate evaporation, is shown by the diagram on page 481. This same diagram illustrates the much more broad and stable base given by the difference between the two vapor pressures, (V-v).

The following diagram presents in graphical form the monthly averages for each lake found in the preceding table, on page 99, for locations on shore.



It is obvious that the method by which these Russell values, for depth of evaporation, were deduced, **does not take into account the exceptional coolness of the water of the Great Lakes, nor the greater velocity of the wind upon their surface, nor their open surface in winter, having a water temperature far warmer than that of the air.**

Professor Russell was unable to work out any definite relations between the mean monthly wind velocity, and the depth of evaporation for the stations in different parts of the United States. He noted that differences in the monthly means of wind velocity at the different localities of Weather Bureau stations in the United States are not large.

Nothing better than Professor Russell's tables has ever been published for showing, in a general way, the conditions affecting evaporation, and the depth of evaporation, month by month, all over the United States; and it is indeed remarkable that with the data available 38 years ago, and with such simple apparatus, estimates of such general reliability could have been thus obtained. His results as adjusted, agreed well with the yearly totals found by Mr. Fitzgerald near Boston.

Professor Russell's exceptionally lucid article in the *Monthly Weather Review* for September, 1888, contains a good summary of what was known about evaporation up to that time, and a description of the Piché instrument of that date, which was simpler than later "improved" forms. The description of his calibration tests upon the Piché evaporimeter, are of interest in showing how far removed this particular investigation of evaporation all over the United States, in 1887–8, based on Piché instruments, was from conditions that control evaporation on the Great Lakes. These Piché instruments were calibrated in the laboratory with great care, by comparison with the loss of weight by evaporation from little tin dishes about 2.5 inches diameter and one-half inch deep, in a closed room.

These tests incidentally showed that after the water became lowered below the rim more than about 1/16 of an inch, the rate of evaporation from the dish rapidly decreased, because of the trapping of the thin layer of cooled and saturated air in the top of the dish.

In other words, the natural rate of diffusion of vapor from the water surface in a small dish, through quiet air, is much less rapid than has been sometimes assumed, and this observation suggests that observations from an evaporation tank of small diameter, or less than 3 feet, which is not kept filled within an inch or two of the top may show a rate much smaller in nearly quiet air, than that from the open reservoir; unless offset to an uncertain extent by the extra evaporation from a wetting of the interior surface of the metallic tank above the water level by capilarity, or by wave motion. In other words, with such a tank, one error must compensate for another error, in order to obtain accurate results.

The Piché instruments, and wet and dry bulb thermometers, at Weather Bureau stations, were all exposed inside standard thermometer shelters; where, as Professor Russell remarks, the velocity of the wind about them was much less than in the open air, perhaps averaging one-third as much. No correction appears to have been made for variations in average wind velocity in different parts of the United States, and in fact he remarks that the differences are not large or controlling. Apparently he let the lessened velocity of the wind within the shelter, compensate for the lesser velocity of wind at nearly the level of the ground, as compared with that at the elevated position of the Weather Bureau instrument. (Over the broad surface of the lake there would be no such lessening of wind velocity.)

Some very interesting experiments on increase of evaporation caused by increasing velocities of wind, were made by suspending a Piché instrument from the arm of the whirling machine used for testing anemometers, in a large, closed room, with the results given in Appendix No. 2.

Such tests were useful for determining the coefficient of a particular instrument, but are not sufficiently accurate for determining the law of evaporation in proportion to wind velocity, because at high velocities the texture of the thin filter paper disc, which exposes water to evaporation in the Piché instrument, failed to conduct water from the reservoir with sufficient rapidity; and because the partial barometric vacuum in the closed reservoir tube of the instrument when largely drawn down, also lessened the rate of delivery from tube to filter paper.

SECOND METHOD

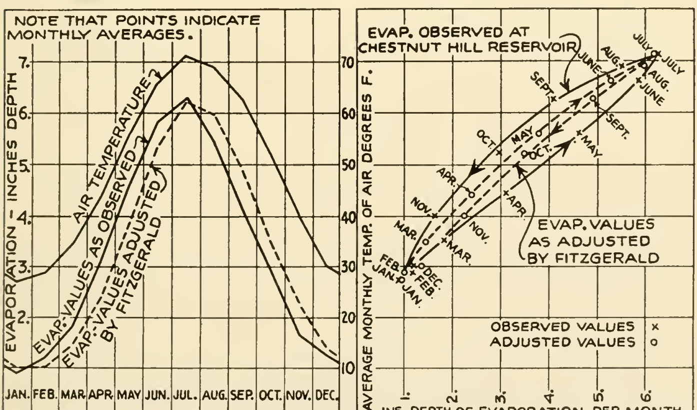
Estimate of Evaporation Based on Mean Temperature of Air in each Calendar Month

The method in ordinary use for estimating evaporation from a lake or reservoir, in absence of direct experiment upon tanks floating in the reservoir under investigation, is to base the estimate upon the record of average temperature of air adjacent to the reservoir in each calendar month, by applying this air temperature to a diagram which shows what has been found evaporated at about the same time of year from floating tanks elsewhere, under the same temperatures.

In general, at most locations, the mean temperature of the water in a shallow tank, or near the surface of a reservoir, averages very nearly the same as the temperature of the air, although its range of fluctuation from hour to hour is much less in the water than in the air, since on this small level surface as for the surface of the earth broadly, the extra heat from the sun by day balances the loss by radiation at night.

This similarity or equality of mean daily temperatures, in many cases, permits the mean temperature of the air to be used instead of the mean temperature of the water, which is especially convenient, because mean monthly air temperature records are nearly always available, while those from the water seldom are.

This method was developed 40 years ago by Mr. Desmond Fitzgerald of Boston, who discovered the remarkable relation shown on the diagram at the left, below.



RELATION OF EVAPORATION TO AIR TEMP. IN EACH CALENDAR MONTH
BY DESMOND FITZGERALD - OBSERVED AT BOSTON

He noted the remarkable way in which the curve of depth of evaporation month by month followed the temperature curve at the neighboring Weather Bureau Station. This naturally suggested that evaporation from a reservoir surface elsewhere, **could be estimated from the mean monthly temperature of the air, at localities under similar climatic conditions, of wind, temperature and humidity.**

The only data suitable for use in estimating the evaporation from the Great Lakes by this second method which the present writer has been able to find in course of a diligent search through technical literature, are listed in the table below and have been combined in the following diagram, on which a mean line has been drawn while studying the circumstances at each data station, as related to conditions over the lakes.

The details regarding the quality of each item of data used, are given in Appendix No. 2.

Space is taken here only sufficient to state that the data used was obtained by measurements of evaporation from floating tanks in reservoirs, as follows:

(1) Ten years observation by Desmond Fitzgerald near Boston (confirmed by measurements of loss from nearby reservoirs),

(2) Thirty-two years records at the water supply distributing reservoir in Rochester, N. Y.,

(3) Sixteen years observations on tank floating in shallow pool at the University of North Dakota,

(4) Nine years observation at Grand River Lock, Wisconsin,

(5) Twelve years observation at Keewatin, Lake of the Woods; 240 miles westerly from Lake Superior, under somewhat different climatic conditions.

Observations in Colorado and California were excluded after careful consideration because of the obvious great differences in climatic conditions, such as dryness of air, rainfall, and altitude, and in the differences thereby caused in insolation by day and radiation at night.

Evaporation is fundamentally a question of heat, and its quantity is a measure of these differences between insolation and radiation as modified by storage of Btu. in the water, or as hastened by the wind and lessened by cloud, fog, and ice.

The mean temperature of air and water in each calendar month, also the total average depth of evaporation found at each data station, and the relative humidity when observed, all are given in the following table.

An additional column is added to the Boston and Rochester data for comparison, and for showing the degree of accuracy with which the formula, $E = (V-v)\ (0.5 + 0.05W)$, (described on a later page) derived from these data for estimating the evaporation from the Great Lakes, will apply at these data stations. Data on humidity and wind are lacking for testing this formula by observations at University of North Dakota and at Grand River Lock.

DATA FOR ESTIMATING EVAPORATION

MEAN MONTHLY DEPTH OF EVAPORATION OBSERVED ON FLOATING TANKS
TEMPERATURES IN DEGREES, FAHRENHEIT

	Boston (Fitzgerald)						Rochester, N. Y. 34 years (Water Works) (1891–1924)							
Month	Average Wind Weather Bureau Miles per Hour	Mean Temperature of Air a.	Aver. Temperature of Water in Reservoir	Relative Humidity	Inches Depth of Evaporation	Computed Evaporation J. R. F. b.	Average Wind at Res. Miles per Hour	Relative Humidity	Mean Temperature of Air	Difference Air and Water in Tub	Aver. Temperature of Water in Tub.	Aver. Temperature of Water in Reservoir c.	Inches Depth of Evaporation	Computed Evaporation J. R. F. d.
Jan.	11.6	27.0	32.8	71.5	0.90	1.05	7.4	76.0	25.3	+7.6	32.9	32.7	0.86	0.89
Feb.	11.7	28.5	32.4	69.0	1.20	1.12	7.4	76.5	24.2	+8.2	32.4	32.2	0.86	0.75
Mar.	11.9	34.5	36.4	69.0	1.80	1.85	7.5	72.5	34.4	+1.8	36.2	34.8	1.67	1.88
April	11.0	44.0	46.5	67.5	3.10	2.94	7.0	67.5	46.7	—0.1	46.6	43.4	2.39	2.61
May	10.1	56.0	58.6	70.0	4.61	4.20	5.7	67.0	59.6	—1.5	58.1	54.1	3.45	3.45
June	9.4	66.0	67.9	71.5	5.86	5.20	4.7	67.0	69.8	—2.0	67.8	63.9	4.38	4.24
July	8.6	71.0	72.3	71.0	6.28	5.85	4.3	68.0	74.4	—2.0	72.4	69.7	4.80	4.80
Aug.	8.4	69.0	71.3	74.5	5.49	5.20	4.3	70.5	71.9	—0.6	71.3	70.5	4.54	4.76
Sept.	8.7	62.5	65.6	76.5	4.09	4.40	4.6	74.0	65.3	+0.3	65.6	65.7	3.54	3.70
Oct.	9.6	52.0	53.6	73.5	2.95	3.00	5.2	75.0	53.3	+1.2	54.5	56.1	2.60	2.78
Nov.	10.7	40.0	42.8	73.0	1.63	1.60	6.4	75.0	40.0	+2.9	42.9	45.5	1.46	1.51
Dec.	11.1	30.0	34.3	71.0	1.20	1.19	6.8	76.5	29.2	+5.2	34.4	36.5	1.21	0.98
Total 12 Mo's	....	....	....	....	39.11	37.60	....	....	....	....	....	....	31.76	32.35
Average	10.2	49.2	51.2	71.5	....	....	6.0	72.0	49.5	+1.8	51.3	50.4	....	....
Total 8 months April—Nov. Incl.	....	....	....	....	34.01	32.39	....	....	....	....	....	....	27.16	27.85

The mean temperature of the air for 24 hours is commonly derived from the average of the readings of maximum and minimum thermometers.

a. The Boston air temperatures were measured at Weather Bureau Station on top of Post Office, about 5½ miles away from reservoir, where observation has shown summer mean temperatures of air average about 1° F. lower than at this reservoir.

b. Wind velocity at reservoir surface is assumed to be 0.56 of that observed at the Weather Bureau at Boston. This ratio was obtained by comparison of observations made at Reservoir and at Weather Bureau July 4th to 31st, 1885.

Temperature of water or ice and snow for months of November, December, January and February is assumed same as that of the air.

c. Temperature of water in the Rochester reservoir averages about 4.0 degrees cooler in May and June than in floating tub of indurated fibre about 15 inches diameter, but becomes of about the same temperature in September.

d. Temperature of water or ice and snow at Rochester for months November, December, January and February is assumed same as for air.

	University of North Dakota (1905–20)			Grand River Lock, Wisconsin (1905–13)			Lake of the Woods, Keewatin, Ont. (1913–1924)						
	Average Temp. of Water in Tank, 7 p. m.	Mean Temperature of Air	Inches Depth of Evaporation	Mean Temperature of Air	Average Temperature of Water in Tank	Inches Depth of Evaporation	Average Wind Miles per Hour	Mean Temperature of Air	Relative Humidity	Difference Air and Water in Tank	Temperature of Water in Tank	Temperature of Water in Lake	Inches Depth of Evaporation (1913–1925)
Jan.	—	—	—	—	—	—	5.04	—0.9	—	—	—	32.1	—
Feb.	—	—	—	—	—	—	5.25	4.7	—	—	—	32.0	—
Mar.	—	—	—	—	—	—	6.03	19.6	68.9	—	—	32.3	—
April	42.2	44.8	3.29*	45	48.4	2.83*	6.22	37.1	66.1	—	—	35.9	0.30
May	54.7	52.4	4.32	54	59.9	4.35	6.58	50.9	59.4	—2.7	48.2	45.5	1.66
June	66.1	63.5	4.94	64	72.0	5.52	5.91	61.1	62.9	+1.0	62.1	60.7	2.40
July	73.1	67.9	5.69	68	74.4	5.74	5.62	66.5	66.2	+3.4	69.9	69.7	3.22
August	68.1	65.4	4.93	65	71.0	4.46	5.46	64.4	66.3	+4.7	69.1	68.6	3.60
September	57.4	56.8	3.61	59	64.5	3.45	6.85	55.5	67.7	+5.9	61.4	61.3	2.98
October	44.9	45.8	2.18	48	50.6	2.22	6.50	42.7	72.6	+7.1	49.8	50.2	2.13
November	33.2	35.0	0.63*	41a	42.7	1.09*	6.52	26.1	78.4	+14.2	40.3	37.3	0.72
December	—	—	—	—	—	—	5.54	9.2	84.1	—	—	32.2	—
Total for 12 months	...	...	—	...	...	—	...	...	...	...	...	...	—
Average	—	—	...	—	—	...	5.96	36.4	—	—	—	46.4	...
Total 8 mo. April–Nov., inc.	...	...	29.59	...	...	29.66	...	...	...	...	...	...	17.01

This assumption is based on the fact that the observed values for the winter months represent the evaporation from ice and snow, the temperature of which will follow that of the air more closely than that of the water because this ice and snow is contained in a tub held entirely out of the reservoir to prevent its freezing in place and to allow the tub and its contents to be taken inside a shelter and weighed to determine the loss due to evaporation.

*Observations April and November at University of North Dakota and November at Grand River Lock, are for parts of month.

At Keewatin, during the seven ice-free months, water temperature in lake averaged 1.2 degrees lower than in floating tank.

There appears to be some uncertainty as to the precise hour at which the rapidly changing temperature of the air at Keewatin was measured. Schedule time must be closely followed in order to get correct values for the 24-hour mean. Measuring the morning temperature one or two hours late might change results materially.

In general, the average of maximum and minimum thermometers for the 24 hours will give a more accurate mean than an average of two observations at say 7 a. m. and 7 p. m. or other specified hours.

At University of North Dakota it was found at the hour of observation, 7 p. m. that temperature of water inside the tank was always substantially the same as in the reservoir outside the tank. At this hour the lines of air and water temperatures cross.

The amount of dependable data, for estimating evaporation from a broad,deep lake, which can be found in an exhaustive search through textbooks and technical periodicals, and in which all of the controlling facts have been accurately measured, is surprisingly small.

In the following studies a strong effort is made to avoid unsupported hypotheses about forces which influence evaporation, and to stick close to the only dependable observations.

RELATION OF EVAPORATION FROM SMALL TANKS TO EVAPORATION FROM RESERVOIRS AND LAKES

It is well known that in a small evaporimeter tank of galvanized iron, of the Weather Bureau pattern 4 feet in diameter with water 8 inches deep, exposed on a platform above the ground and exposed to sun and air on its sides, the water becomes heated by the sun by day, and cooled at night to a much greater extent of change than water in a reservoir, and that the depth of evaporation becomes thereby largely increased, commonly to the extent of 25% or 33%; but it has been assumed as highly probable that in a floating tank about 3 feet or more in diameter, **set within a reservoir,** that the water would maintain substantially the same average temperature as that within the upper part of the reservoir, and that the depth of evaporation would be the same in both tank and reservoir; but there are certain minor differences to be taken into account.

The differences in depth of evaporation from tanks of different diameters and of different exposure of exterior to sun and air, were measured in some excellent experiments at the Agricultural Experiment Station at Denver, Col. described later, on pages 433 to 437.

In these Denver experiments, **the Standard Weather Bureau pan was found to show about 50 per cent more evaporation** than that from the tank floating in a reservoir, as commonly used by hydraulic engineers.

(1) Unless the floating tank is at least 3 feet in diameter, and perhaps if less than 5 feet, and particularly if tank is not kept so full as to prevent any pocket beneath the top edge of its rim, a thin vapor blanket persists, comprising chilled and nearly saturated air, that may lessen the evaporation to an important degree in hours when wind is not strong.

This lessening of evaporation in a tank that is too small, or which presents an air pocket in its top, may in many cases be offset, or exceeded, by the increased evaporation from the thin vertical film of water drawn up on the inner sides of the tank, by capilarity, or washed up as the floating tank is jostled by waves. **Accuracy demands extreme care.**

(2) The temperature of water in the tank commonly differs from 1° to 3° F. from the temperature in the reservoir. In Mr. Fitzgerald's experiments with tanks floated from a raft in midst of reservoir, the differences sometimes were more than this, even in a tank 10 feet in diameter; but the temperatures of tank and reservoir averaged about the same for the 24 hours. They commonly nearly coincided from 9 p. m. to 9 a. m., the water in the tank then became warmer until a little later than noon after which the difference became

gradually less. Since the breeze was commonly stronger by day, when water also was slightly warmer, this tended to slightly larger evaporation, and toward off-setting the effect of any thin local vapor blanket.

In experiments by Professor L. G. Carpenter* at Fort Collins, Col., it was found that the water warmed up quickly in the morning **on top,** but cooled uniformly **through the mass** at night; with the result that the average of observations at 7 a. m. and 7 p. m. was about 3.5° too low. The average of a maximum and minimum thermometer in the water, gave a more accurate average value for the 24 hours, than the mean of observations at 7 a. m. and 7 p. m.

(3) Calms, with any attendant important low lying vapor blanket, are relatively rare on the Great Lakes; wind on the lakes exceeds 3 miles per hour for about 98% of the time.

(4) In time of strong wind, the surface of the Great Lakes becomes roughened with waves, which give increasing exposure of surface, and finally "white-caps" form at about 10 to 15 miles per hour.

Any thin film of saturated, chilled air is dissipated and doubtless the rate of evaporation is very largely increased, under a wind strong enough to give white-caps.

(5) The **use of daily or monthly average values** for temperatures, humidity, and wind, possibly **tends to lessen the amount of evaporation computed** from these data in comparison with that which would be shown if precise hourly observations were available; because **evaporation functions with increasing rapidity** with increase of temperature or high wind, **along curves,** instead of along a straight line.

(6) The locations of observation stations, on the opposite sides of each of the Great Lakes, in the path of the winds, tends automatically to correct for the effect of any possible "vapor blanket" influencing the evaporation at mid-lake.

Evaporation, probably, is largely a sort of instantaneous phenomenon, varying largely from hour to hour, under the varying natural climatic conditions; and data in form of monthly averages, may lead to estimates differing largely from those that would come from hourly observations.

The average monthly temperatures of air found from the Weather Bureau records, for each data station, in each calendar month, and the corresponding computed evaporation have been plotted on the following diagram, and between these scattering points of data a heavy line drawn, so as to take account of relative conditions, so far as practicable, prevailing over the Great Lakes in comparison with conditions at the data stations.

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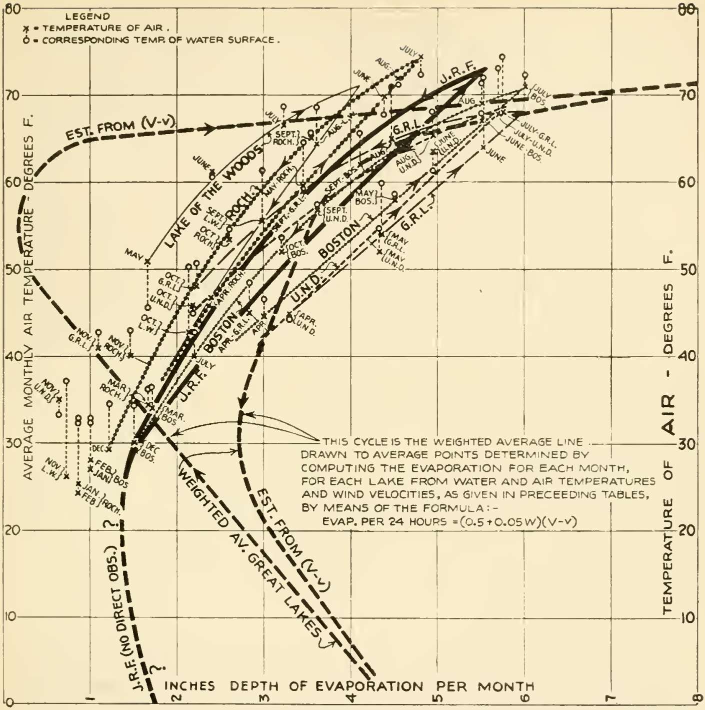
*See page 15, Bulletin 45, Col. State Agricultural College, May 1898.



RELATION OF EVAPORATION TO AVERAGE TEMPERATURE OF AIR

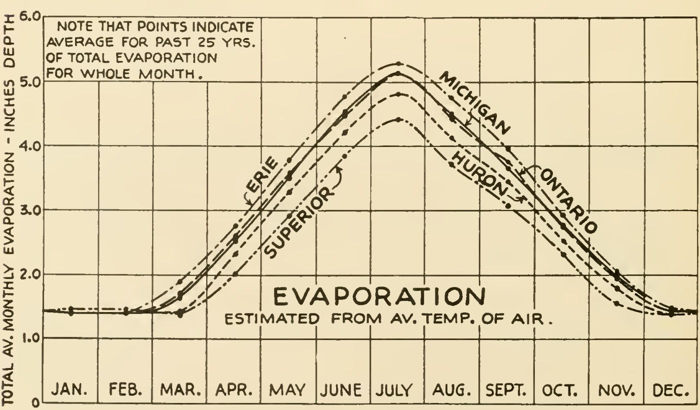
The two loop lines marked "Est. from (V-v)", have been added in order to show the great difference found in an estimate of the evaporation under these same air temperatures, when influenced by the much lower temperatures of the water, and the different humidity found over the Great Lakes, as compared with an estimate of evaporation based upon temperature of air or water alone, as described on a later page, under "Method No. 4."

Total Monthly Evaporation in Inches Depth on Great Lakes Estimated from Temperature of Air

The following values are estimated from table of **monthly mean temperatures of air** for each lake given on page 85, and from the adopted mean line of preceding diagram, showing relation of evaporation to air temperature.

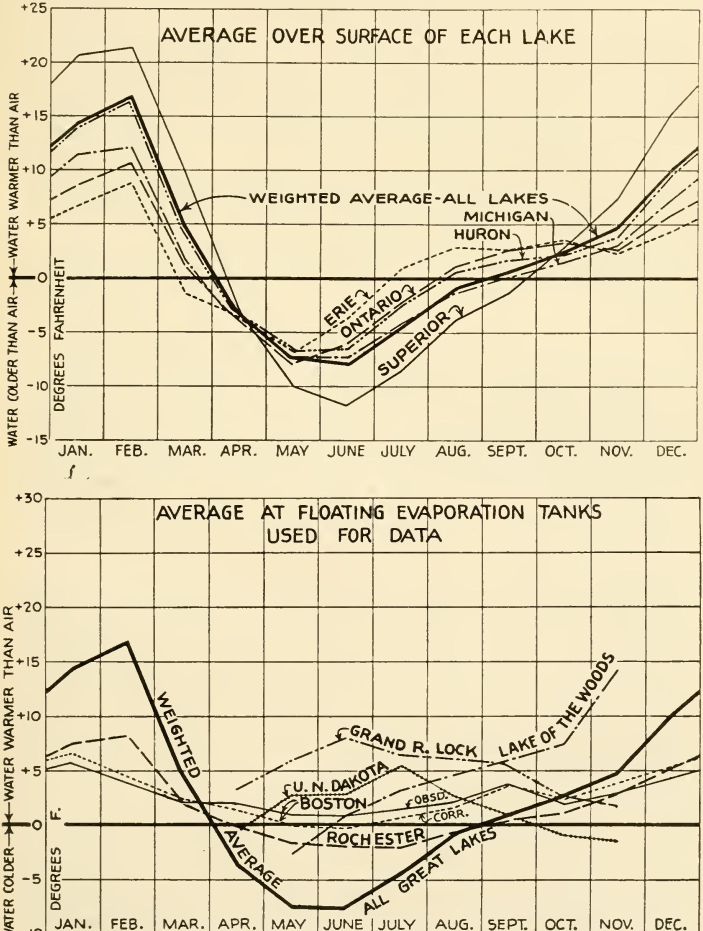
	Lake Superior		Lake Michigan		Lake Huron		Lake Erie and St. Clair		Lake Ontario		Weighted Averages on basis of Area	
Month	Mean Temp. of Air ° F.	Inches Depth of Evap.	Mean Temp. of Air ° F.	Inches Depth of Evap.	Mean Temp. of Air ° F.	Inches Depth of Evap.	Mean Temp. of Air F.	Inches Depth of Evap.	Mean Temp. of Air ° F.	Inches Depth of Evap.	Mean Temp. of Air ° F.	Inches Depth of Evap.
Jan.	11.4	1.45	20.7	1.37	18.1	1.38	25.3	1.39	23.4	1.38	17.7	1.37
Feb.	10.7	1.46	19.9	1.37	15.7	1.40	23.2	1.38	21.3	1.37	16.3	1.39
Mar.	22.2	1.37	31.4	1.65	27.2	1.42	34.4	1.88	31.8	1.68	27.7	1.43
April	35.8	2.00	42.6	2.52	40.0	2.30	44.7	2.72	43.2	2.56	40.0	2.30
May	46.8	2.90	53.3	3.50	50.6	3.25	56.2	3.78	54.0	3.55	50.8	3.26
June	56.7	3.82	63.3	4.49	60.4	4.20	65.7	4.75	63.0	4.45	60.6	4.22
July	62.6	4.42	69.2	5.12	66.5	4.82	71.0	5.30	69.2	5.12	66.5	4.83
Aug.	60.8	3.70	67.4	4.48	64.4	4.10	69.1	4.75	66.9	4.42	64.6	4.12
Sept.	54.4	3.08	60.9	3.70	58.4	3.45	63.3	3.98	61.4	3.76	58.4	3.45
Oct.	44.1	2.32	50.5	2.78	47.8	2.58	52.4	2.92	50.7	2.80	48.0	2.60
Nov.	30.6	1.52	37.8	1.94	35.2	1.77	39.6	2.04	38.4	1.95	34.9	1.76
Dec.	17.7	1.37	25.6	1.40	23.5	1.38	28.6	1.45	27.2	1.42	22.9	1.37
Total Annual	....	29.41	....	34.32	....	32.05	....	36.34	....	34.46	....	32.10
Mean	37.8	....	45.2	....	42.2	....	47.8	....	45.9	....	42.4	....

The inches depth of evaporation thus found, for each calendar month for each lake, by an estimate **based solely upon the temperature of the air at the Weather Bureau Stations**, is shown in the diagram below.



Water Temperature Versus Air Temperature as a Measure of Evaporation

The previous method (which is the ordinary method), implies that the relation of water temperature to air temperature is the same at the lake and at the data stations, and also implies that the dew-point temperature and the wind movement are substantially the same at both. That the temperature relation between air and water, at the lakes is different from that at the data stations, is shown by the diagram below.



COMPARISON OF MEAN MONTHLY TEMPERATURES OF AIR AND WATER

(1) From these diagrams it is seen that the temperature relation, between air and water, is materially different at the lakes from that at the principal data stations.

(2) At all of the Great Lakes the water in mid-summer averages from **7° to 12° cooler than the air,** this difference being greatest at Lake Superior; while at all of the data stations (except Rochester) the water in the floating tank in summer averages **warmer than the air.**

(3) The spring overturn, or time of equalization of air and water temperatures ordinarily occurs about April 1st; and the fall overturn, or equalization, about September 1st; but there are variations of nearly a month.

(4) Through the winter months the water in the lakes is much warmer than the air; this difference in temperatures is far greater than in the tanks at the data stations.

The effects from these differences are discussed in Appendix No. 2.

Cooler Water in Summer Lessens Evaporation from the Great Lakes

The great depth of the lakes, particularly in parts of Lake Superior where the depth is more than 1,000 feet, and in parts of Lakes Michigan and Huron, more than 500 feet deep, presents a vast volume of cold water in the depths at more than 100 feet below the surface, which remains at or near the temperature of maximum density (39.2° F.) throughout the year.

More or less of this cold water is brought to the surface by the reverse currents, deep below the surface, which necessarily are brought into a sort of vertical rotation, in order to balance the surface currents driven before strong winds, and in general, the presence of more or less of water from the depths causes a much greater difference between the temperature of the air and the temperature of the water near the surface, than is found in relatively shallow, artificial reservoirs of 20 to 50 feet in depth, on which the few available observations upon evaporation have been made.

Also, there is up-welling of the deep, cold water caused by the very important currents, or "tides," set in motion by the passing of barometric changes—"highs" and "lows." These currents in meeting the obstruction of shoals or that of an opposing current may **bring cold water to the surface.**

THIRD METHOD

Estimate of Evaporation Based on Average Temperature of Water in Each Calendar Month

The Third method which has been applied in estimating the evaporation from each of the Great Lakes, is similar to the second, but proceeds with **the average monthly temperature of the water,** instead of that of the air, as its basis; because of recognizing that the relation of water temperature to air temperature is very different over the Great Lakes, (particularly over Lake Superior) from that at the reservoirs where data for the second method were deduced; and **because the theory of evaporation shows that the water temperature alone, is of greater influence than the air temperature alone, in determining the amount of evaporation.**

Successive Steps Preliminary to Estimating Evaporation from Water Temperatures

The successive steps in estimating the evaporation at each lake by the "third method," or from the water temperatures by means of present data are as follows:

First, we have the table of surface water temperatures compiled **under the direction of the U. S. Signal Service** by Mr. N. B. Conger, for many years observer of the U. S. Weather Bureau at Detroit, Michigan, at various Weather Bureau stations around the Great Lakes. This table gives the monthly averages of observations at 2 p. m. (or about the hour of maximum surface temperature) for the 13 years, from 1874 to 1886.

The differences between temperatures in the same calendar month, from year to year, in these 13 years, are found small, and the averages for this long term check up well with many scattered observations in more recent years and doubtless represent accurately conditions that would be found at the present time, although the Conger observations were made about 40 years ago.

It is stated that various comparisons with temperatures in mid-lake, or far from shore, at about the same time with the Mr. Conger's data, showed no substantial difference in the averages, although occasionally abnormally low temperatures were found at the surface over localities of great depth, or where currents had caused up-welling.

Further confirmation that the average of these 13 years of daily observations compiled by Mr. Conger, are fairly representative (after a few slight adjustments) of water temperatures throughout the length and breadth of the Great Lakes, is found in the data collected by

Colonel Townsend, and in the data from the Chicago 2-mile crib, and that from the lighthouses and lightships, presented in later pages and given with more detail in Appendix No. 2.

Further confirmation has been made with daily water temperature and adjustment observations made on the U. S. lighthouse tender "Crocus" during its annual cruise over Lake Erie and Lake Ontario during the year 1925. Also from the log of the "Hyacynth" from April to December 1923, 1924 and 1925, in Lake Michigan. Also from the log of the lighthouse tender "Sumac" for the same years. (These engine room logs of the lighthouse tenders do not agree very well in their temperatures of condenser injection water from the lake.)

The weighted averages of all of these values of maximum water surface temperature for the 13 years, month by month, together with the adjustment made to the Conger values, by means of the various other records mentioned, is given in the following table.

These surface temperatures are subject to large and sudden disturbance by wind, which brings cold water up to the surface from the depths. Mr. Conger states that on Lake Superior on one occasion **in mid-August, he sailed nearly all day in water at about 42° F.**

In 1892 the U. S. Weather Bureau issued its first wreck chart of the Great Lakes. Preparation for this chart brought out the importance of studying currents and fogs, and that water temperatures had an important part in causing both.

Special water thermometers were given to about 60 ship masters as volunteer observers, with schedules for observation at 8 a. m. and 8 p. m., 75th Meridian time, while under way.

A large mass of observations were accumulated along the usual course of vessels between the principal ports. Observers elsewhere were very few. The results appear to have received no publication and apparently were never fully digested.

Professor Mark W. Harrington, at that time Chief of the Weather Bureau, gave the matter much personal attention, and with a small party visited Lake Superior and supervised many observations of temperatures at depths of 10, 20 and 100 feet.

Professor Harrington prepared a paper, under the title: "Preliminary Results of Water Temperatures of the Great Lakes for the Seasons of 1893 and 1894," setting forth some of the preliminary results of these observations. It is understood that a paper on "The Currents of the Great Lakes," was to have been delivered by him before the students of the Geological Department of Johns Hopkins University, in 1895. Finding it impracticable to present the subject in person, Professor Harrington sent his manuscript and illustrations to Prof. Geo. B. Shattuck and the latter presented the subject to the students.

One of his preliminary conclusions of interest was that the isothermal lines of water temperatures followed very closely the depth contours of the lake, and the coolest water in summer being found over the central portions of the Great Lakes; and that over the central portions of Lake Superior the mid-summer temperature was only about 40°, while it was 60° at the innermost ends of the bays, with rapid change near the shore.

Unfortunately this paper, giving the results of the many observations on water temperatures and currents, with its maps and isotherms seems never to have been printed. A manuscript copy was loaned the writer by Mr. N. B. Conger, in charge of the U. S. Weather Bureau station at Detroit, Michigan.

Also adjustment was made, where necessary, to give weight to the other data upon water surface temperatures, presented in the tables in Appendix No. 2, and for temperatures in mid-lake observed by lighthouse tenders.

Separate maps of isotherms were sketched for the summer months of maximum evaporation, for the winter months of minimum evaporation, and for spring and fall. Also, a map of the mean annual water isotherms was drawn. These maps were similar to those given for the air isotherms reproduced on a small scale on the preceding page. The net amount of these adjustments, which also is small, is shown in the table on the next page.

Second. The next step is the plotting of the relations found at experimental stations between the monthly total depth of evaporation and the mean monthly temperature of the water surface. The diagram thus prepared of total monthly evaporation corresponding to a given water temperature, is very similar to that previously prepared for relation between depth of evaporation and mean temperature of the air, and is presented below.

The available stations giving th se data are few, and much consideration has to be given to the relative weight of different data, and to selecting that most applicable to conditions found over the greater depths of the Great Lakes. The diagram on page 111 is useful in bringing out differences in condition which doubtless affect the quantity evaporated.

The line for depth of evaporation at temperatures below maximum density, is drawn to give larger values for winter evaporation than generally given in the text books, because of the open surface of the lakes throughout the winter, because of the facts elsewhere quoted from Mr. Fitzgerald's experiments, and from certain theoretical considerations based on the table of computed vapor pressure differences, corresponding to mean monthly temperatures and humidities over the lakes. (These matters are discussed at length in Appendix No. 2.)

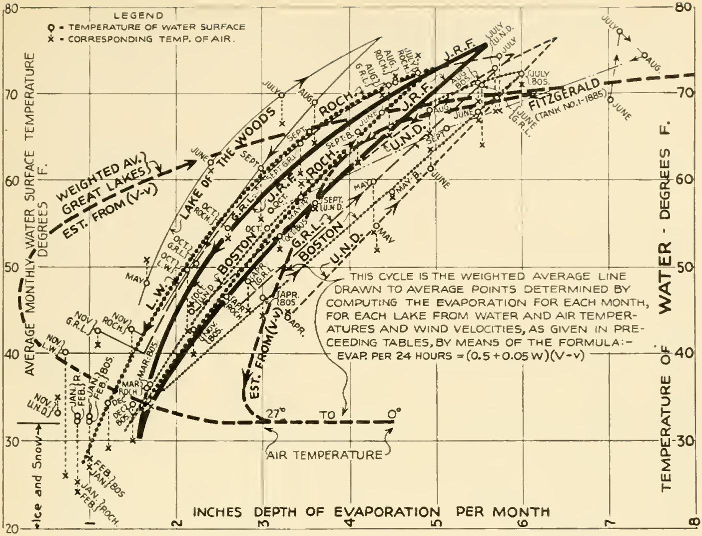
The source of data on water temperatures is described more at length in Appendix No. 2.

AVERAGE WATER SURFACE TEMPERATURES IN THE GREAT LAKES

(Compensated for Time of Observation and Location and After Giving Due Weight to Other Observations Mentioned Above.)

	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Average
Average of Conger's Records for Duluth and Marquette	32.1	32.0	32.4	36.0	41.0	50.8	58.8	63.0	57.1	49.1	40.5	33.7	43.9
Deduct to correct from 2 p. m. to 24-hour Mean	0	0	0	2.0	3.0	3.0	2.0	1.0	1.0	0	0	0	1.0
Deduct to correct for location of stations	0.1	0	0.4	1.0	1.0	2.8	2.8	5.0	3.1	2.1	2.5	0.7	1.8
Average Water surface temperature for Lake Superior	**32.0**	**32.0**	**32.0**	**33.0**	**37.0**	**45.0**	**54.0**	**57.0**	**53.0**	**47.0**	**38.0**	**33.0**	**41.1**
Average of Conger's Records for Escanaba, Milwaukee, Chicago and Grand Haven	32.3	32.4	33.9	42.5	52.9	61.8	67.9	69.5	63.2	53.4	41.5	33.0	48.7
Deduct to correct from 2 p. m. to 24-hour Mean	0	0	0	2.0	3.0	3.0	2.0	1.0	1.0	0	0	0	1.0
Deduct to correct for location of stations	0.3	0.4	0.9	2.5	3.9	2.8	0.9	2.5	1.2	1.4	0.5	0	1.4
Average water surface temperature for Lake Michigan	**32.0**	**32.0**	**33.0**	**38.0**	**46.0**	**56.0**	**65.0**	**66.0**	**61.0**	**52.0**	**41.0**	**33.0**	**46.3**
Average of Conger's records for Alpena and Detroit	32.2	32.0	33.0	41.5	53.6	64.4	70.9	70.5	64.0	52.9	40.3	32.8	49.0
Deduct to correct from 2 p. m. to 24-hour Mean	0	0	0	2.0	3.0	3.0	2.0	1.0	1.0	0	0	0	1.0
Deduct to correct for location of stations	0.2	0	-1.0	3.5	5.6	6.4	4.9	4.5	3.0	2.9	1.3	+0.2	2.7
Average water surface temperature for Lake Huron	**32.0**	**32.0**	**32.0**	**36.0**	**45.0**	**55.0**	**64.0**	**65.0**	**60.0**	**50.0**	**39.0**	**33.0**	**45.3**
Average of Conger's Records for Toledo, Sandusky, Cleveland and Buffalo	32.8	32.2	34.6	45.9	57.2	68.5	75.2	74.1	68.3	57.1	43.3	33.6	51.9
Deduct to correct from 2 p. m. to 24-hour Mean	0	0	0	2.0	3.0	3.0	2.0	1.0	1.0	0	0	0	1.0
Deduct to correct for location of stations	0.8	0.2	1.6	2.9	5.2	3.5	2.2	2.1	1.3	1.1	1.3	0.6	1.9
Average water surface temperature for Lake Erie	**32.0**	**32.0**	**33.0**	**41.0**	**49.0**	**62.0**	**71.0**	**71.0**	**66.0**	**56.0**	**42.0**	**33.0**	**49.0**
Average water surface temperature for Lake Ontario Obtained from isothermal maps drawn for each month.	**32 0**	**32.0**	**33.0**	**39.0**	**46.0**	**57.0**	**67.0**	**68.0**	**64.0**	**54.0**	**41.0**	**33.0**	**47.2**

An additional adjustment is required for locations of the stations used by Mr. Conger, which were all on the United States side of the Lakes, farther south than the average exposure of lake surface. For determining the amount of this adjustment, a series of maps of the water isotherms over each lake were drawn from the data in the Conger table, after adjustment from maximum daily value to mean value for 24-hours.



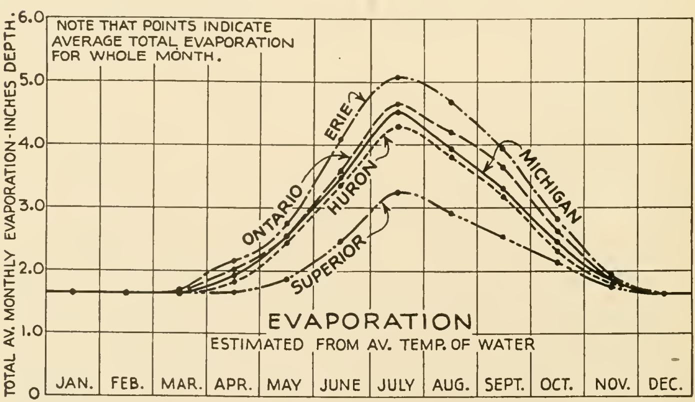
RELATION OF EVAPORATION TO AVERAGE TEMPERATURE OF WATER SURFACE

Third. By means of the above diagram, the following table of probable total depths of evaporation in each month from each lake, from records of temperatures of the water surface has been prepared.

Total Monthly Evaporation in Inches Depth on Great Lakes Estimated from Temperature of Water

Month	Lake Superior		Lake Huron		Lake Michigan		Lake Erie		Lake Ontario		Weighted Average on basis of	
	Temp. of Water °F.	Inches Depth of Evap.	Temp. of Water °F.	Inches Depth of Evap.	Temp. of Water °F.	Inches Depth of Evap.	Temp. of Water °F.	Inches Depth of Evap.	Temp. of Water °F.	Inches Depth of Evap.	Temp. of Water	Inches Depth of Evap.
Jan......	32.0	1.62	32.0	1.62	32.0	1.62	32.0	1.62	32.0	1.62	32.0	1.62
Feb......	32.0	1.62	32.0	1.62	32.0	1.62	32.0	1.62	32.0	1.62	32.0	1.62
Mar......	32.0	1.62	32.0	1.62	32.0	1.65	33.0	1.65	33.0	1.65	32.4	1.64
April....	33.0	1.65	36.0	1.80	38.0	1.93	41.0	2.15	39.0	2.01	36.3	1.83
May.....	37.0	1.87	45.0	2.45	46.0	2.45	49.0	2.71	46.0	2.45	43.1	2.24
June.....	45.0	2.45	55.0	3.35	56.0	3.45	62.0	4.05	57.0	3.55	52.8	3.06
July.....	54.0	3.25	64.0	4.28	65.0	4.50	71.0	5.06	67.0	4.62	61.9	4.09
Aug......	57.0	2.90	65.0	3.80	66.0	3.92	71.0	4.68	68.0	4.74	63.5	3.70
Sept......	53.0	2.52	60.0	3.20	61.0	3.30	66.0	3.94	64.0	4.28	58.9	3.07
Oct......	47.0	2.12	50.0	2.30	52.0	2.45	56.0	2.80	54.0	2.62	50.4	2.35
Nov......	38.0	1.73	39.0	1.78	41.0	1.84	42.0	1.88	41.0	1.84	39.6	1.78
Dec......	33.0	1.60	33.0	1.60	33.0	1.60	33.0	1.62	33.0	1.60	33.0	1.60
Mean....	41.1	..	45.3	..	46.2	..	49.0	..	47.1	..	44.7	..
Total....	..	24.95	..	29.42	..	30.35	..	33.78	..	32.60	..	28.60

Fourth. These tabular values are plotted in the diagram below giving the estimated evaporation month by month for each of the Great Lakes in a form similar to that on page 110, derived from temperature of air over each lake.



FACTORS OMITTED IN PRECEDING METHODS

The three methods presented above omit all account of difference in velocity of wind over the lakes, from that at the data stations.

Nevertheless, **if given a proper experimental foundation,** the Russell formula used in the first method, seems logically better than the second method, since it takes account of the dryness of the air, or its readiness to receive moisture, by taking account of the dew point instead of depending mainly upon temperature of air, and reference to the diagram of the Fitzgerald observations on page 481, will show that the amount of evaporation closely follows the difference between water temperature and dew point temperature.

The third method, depending chiefly on temperature of water, is certainly more logical than the second, which depends mainly on temperature of air, and it is suggested that a method on the Russell plan, which made use of the water temperature (by using the wet-bulb temperature of the air), and the dew point temperature of the air, would be still better; but since all three of the above methods neglect the important factor of variation of force of wind, it seems better, after a study of wind conditions, to go back to the methods of Dalton, and the fundamental physical laws, as will appear on later pages.

The Greater Force of Wind Tends to Increased Evaporation

The broad sweep and great force of winds over the Great Lakes cause an intimate and forceful contact between wind and water, far greater than that found on the few reservoirs and tanks from which evaporation has been accurately measured. Such records as are available indicate that the **mean velocity of the wind at the surface of the Great Lakes averages more than double that at the data stations,** at Boston, Rochester, etc.

There is little definite knowledge available about the relation of the velocity of the wind at the water surface over the Great Lakes to the velocity of the wind at the Weather Bureau stations on their shores. These Weather Bureau anemometers are at altitudes which vary from 55 feet to 570 feet above the adjacent lake, and anywhere from 20 feet to 100 feet above the irregular roof lines of adjacent buildings, which cause irregular gusts and eddies in the lower levels of the air.*

It is plain that the elevation of these anemometers must be reckoned from the general roof level and not from the ground. In some

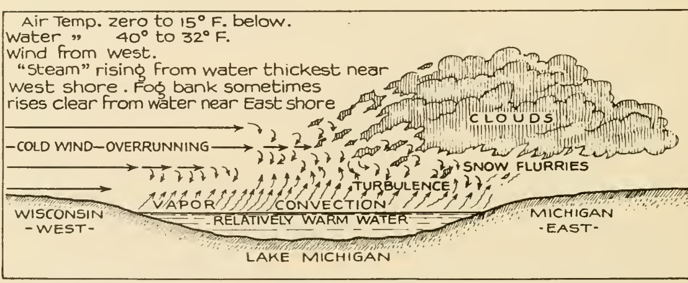
*The writer has been much impressed with the irregularity of air currents shown by snow falling through a strong wind passing over city roofs, as seen from an upper window in a tall building. This turbulence, as in water, may extend far above the rough channel-bed.

cases the disturbance of air currents may reach high enough to retard the velocities observed, although locations for these Weather Bureau instruments have been sought on the highest buildings available.

Regarding the prevalence of wind and calm, and the possibility of a low vapor blanket, close to the surface of the water, which might hinder evaporation, we may note that while discussing another matter Mr. Wm. T. Blunt, for many years a U. S. Assistant Engineer connected with the Lake Survey work, has stated that for 98 per cent of the time the velocity of wind upon the Great Lakes exceeds 3 miles per hour, equivalent to 4.4 feet per second. At U. S. Weather Bureau Stations about the lakes the monthly average seldom falls below 7.5 miles per hour, and **for the 12 months averages 10.5 miles per hour,** and during severe storms reaches 50 or more miles per hour.

In comparison with conditions at some small distance inland, on the windward side, there always is a surplus of vapor in the air over the lakes, sometimes visible in fog, but more often invisible, which **is effective in lessening radiation at night, and in trapping warmth from the sun by day;** but this also spreads out and envelops the Weather Bureau station on the leeward shore. The fog records in the table on page 88 are all from observations at the stations where temperature and humidity of air are observed.

The effects of this one-sided vapor blanket upon the humidity and vapor pressure differences, which primarily cause evaporation over the Great Lakes, are included to an important extent in the observations recorded at the Weather Bureau stations on their borders, because for about half of the time the wind reaching these stations has come across the lakes.



FORMATION OF HIGH VAPOR BLANKET OVER LAKE MICHIGAN.

The sketch on the preceding page is copied from the *Monthly Weather Review* of September 1921, page 503, to illustrate the vapor blanket which sometimes forms over the lake and extends inland on the leeward side, so as to affect temperatures, and humidity; leaving an impress in the records of the Weather Bureau Stations on the leeward side; the leeward records naturally showing cooler air temperature and higher humidity in summer, but showing warmer air temperature in winter, or a condition different from that on the windward side.

Across Lake Michigan from Milwaukee and Matinowoc to Grand Haven and Ludington, conditions like those shown in the sketch are sometimes found with clear skies on the windward shore, when winds at from zero to 15 degrees below zero F., sweep across the lake and cause snow flurries, which extend from a few miles off shore to 5 or 10 miles inland; their extent depending on relative temperatures of air and water.

The captains of the railroad car ferries note that under these conditions, as they leave the westerly shore, "steam" or fog will be found rising from the water, which under conditions of early-December will lift as the easterly shore is approached, but in the more intense cold of air and water later in the winter, this "steam," or fog, may extend all of the way across the lake.

The meteorologist reports that under these conditions, evidently there is a low, thin layer of warmer air close to the water near the westerly shore, which increases in thickness toward the east as more vapor is gathered, until convectional currents and turbulence set in. The vapor blanket is manifest in the form of visible vapor rising near the western shore, overhanging in clouds farther out in the lake, and eventually in precipitation in the form of snow flurries over the eastern shore, extending from 10 to 20 miles inland; **while weather is clear on all sides, farther from the lake.**

Somewhat similar conditions are reported by the Weather Bureau observers at various stations around the Great Lakes.

At times, when the station instruments on opposite sides show important differences of air temperature and humidity concurrent with the wind, it is plain there must be a small difference in the rate of evaporation upon the two sides of the lake. An attempt has been made to compute this difference approximately from the observations at Milwaukee and Grand Haven on pages 475 and 477. The difference for the whole year from the means already computed is not large, and until we have more precise data on evaporation all around the lakes, it seems inexpedient to try to correct for it, because the averaging of air temperatures, water temperatures and dew point temperatures already made, in obtaining mean monthly values for each lake, has taken some account of these facts; leaving as an open question the rate at which the evaporation becomes less in going across the lake. Probably at mid-lake the rate is not precisely a mean between that at the two sides.

When considering the possible effect of a high vapor blanket, in lessening evaporation over the Great Lakes one may recall that the Boston observations, which are the most precise data available for giving relations of monthly depth of evaporation to temperature and to vapor pressures, were made not many miles back from the Atlantic ocean, and within the influence of vapor-laden winds from the Northeast, East and Southeast.

The possible effect of a vapor blanket is discussed at greater length in Appendix No. 2 and the extent and frequency of dense fogs are described on pages 87 to 91.

RATIO OF WIND VELOCITY ON LAKE TO VELOCITY AT WEATHER BUREAU STATION

This matter of the relation of velocity of wind at the reservoir surface in relation to that observed at Weather Bureau stations is of high importance to a correct interpretation of formulas for evaporation.

Some of the text books and essays on evaporation present questionable guesses about this relation, when they state that the velocity at lake or reservoir level is only one-half or one-third that at the elevated anemometers of the Weather Bureau stations.

Thomas Russell, Professor of Meteorology in the Weather Bureau, formerly a United States Assistant Engineer on the Lake Survey, and a writer of note on hydrology and meteorology, whose statements carry exceptional authority, says in chapter 5, page 105 of his treatise on "Meteorology;"

> "At the Chicago water-works crib, three miles out in Lake Michigan, the velocity is **twice as great** as on top of a high building in the city."

He also states that "over the sea the velocity is much greater than at the same height over the land."

The following is from "Weather and Climate of Chicago," page 288, 1914, University of Chicago Press.

The result of a short comparison between a wind gage located 60 feet above the surface of Lake Michigan near the Life Saving Station on the breakwater at the mouth of the Chicago River, beginning August 1911, compared with the official Weather Bureau wind gage on the Federal Building 310 feet above the ground and 320 feet above the lake, showed wind movement at the breakwater gage almost uniformly **higher than at the Weather Bureau office.**

The average for the year ending July 12 was 14.1 miles per hour for the breakwater anemometer and 13.4 miles per hour for the Federal Building, although the latter has 263 feet greater elevation.

There was a great difference in the relations when winds were off the free surface of the lake as compared with winds off shore.

The official Weather Bureau anemometer recorded much lower velocity in strong winds, than at the breakwater. For example, February 17, 1912, with a northwest wind from off the lake, the breakwater gage gave 33.1 miles per hour compared with 21.0 miles per hour for the Weather Bureau gage on the Federal Building.

With winds from off the lands on January 15, 1912, the breakwater gage gave 19.5 miles per hour and the Federal Building gave 20.3 miles per hour.

This ratio of wind velocities is discussed at greater length in Appendix No. 2.

Correction of Anemometer Readings

The readings of the standard form of Robinson anemometer used by the U. S. Weather Bureau require correction for precise work at velocities greater than 10 miles per hour; but the amount of this correction within the range of velocity under consideration in the present study is of no significance.

The experimental determinations on the whirling machine of the U. S. Weather Bureau at Washington in 1907, were as follows:

Velocity by Register, miles per hr.	5.0	10.0	15.0	20.0	25.0	30.0	35.0	40.0	45.0	50.0	60.0	70.0	80.0
Actual Velocity	5.1	9.6	13.8	17.8	21.8	25.7	29.6	33.3	37.1	40.8	48.0	55.2	62.2

LACK OF ICE-COVER ON GREAT LAKES LARGELY INCREASES EVAPORATION

The Great Lakes mostly remain without ice-cover all through the winter. In the later part of the winter large fields of ice form on the shores of all of the lakes, and at times these break loose and drift with the wind; but in general **the percentage of the entire surface covered by ice on any of the Great Lakes is extremely small.** It is reported that in 1843 Lake Superior was completely frozen over, but prior to the development of airplanes there was no way of being sure that such a statement was true.

The extreme western end of Lake Erie has been frozen over near Kelly Island so that sleighs have crossed.

The ice cover is reported relatively larger on Lake Erie than on the other lakes; and because of its relative shallowness, this lake freezes earlier than the others.

The extreme northern parts of Lakes Michigan and Huron are said to sometimes become completely covered with ice, but the percentage of the entire lake that is covered probably is not large. The danger of venturing out far from the shore to explore an ice field is well known all around the lakes, and lives have been lost by a sudden shift of the wind that have set large fields of ice adrift. Such data as could be found are given on pages 91 to 96.

During the winter, the vast open surfaces of the lakes, within which water cannot fall below 32 degrees in temperature, is exposed to air that may be of zero temperature, or much lower than zero in the Lake Superior region, and **this condition certainly must cause abnormally high winter evaporation,** for which we have no precedent at the data stations.

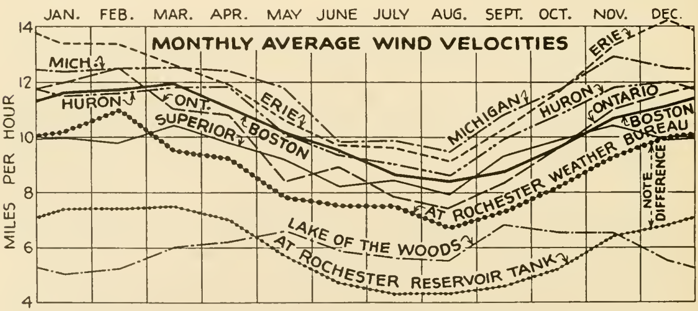
COMPENSATION FOR DIFFERENCES IN WIND AND VAPOR PRESSURE

The three methods described in preceding pages of estimating evaporation from the Great Lakes, in each calendar month, from the mean temperature of the air, or of the water, recorded during that month, imply that wind and humidity (or rather, vapor pressure differences) are substantially the same at the reservoir or lake in question as at the data stations.

The following diagram shows that the wind movement over the Great Lakes, judged by Weather Bureau stations on their shores, averages materially larger than the wind movement at the data stations. A correction should be made for this, as follows, **if we accept the Weather Bureau record as fairly representative of the velocity at the water surface,** until more definite comparative measurements have been made.

The Boston record, plotted in the following diagram, is that at the Weather Bureau Station which is probably from 50 to 80 per cent larger than that at the Boston data tank.

Also, on this diagram, the wind at Lake of the Woods is seen to be of much slower velocity than that over the Great Lakes, or at the Boston data station, and this helps account for its low evaporation record.



COMPARISON OF WIND VELOCITIES
AT DATA STATIONS AND U.S. WEATHER BUREAU STATIONS AROUND GREAT LAKES

According to the formula on a following page, the effect of the wind may be represented by the second factor in the following equation in which W is the velocity of wind in miles per hour:

$$E = (V\text{-}v)\ (0.5+0.05W)$$

An increase in average wind movement from about 10 miles per hour, at the Weather Bureau stations shown by the diagram above, to 20 miles, for the average over the lakes, would increase the evaporation in ratio of

$$\frac{0.5+0.1}{0.5+0.5}=\frac{1.5}{1.0}=1.50$$

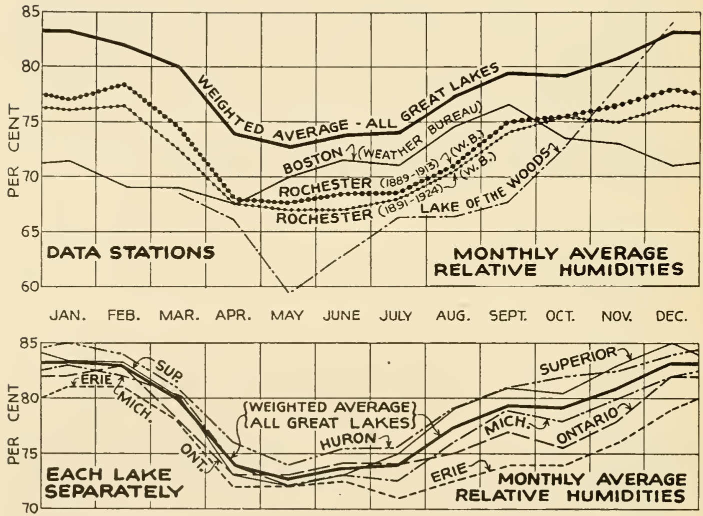
or would give 50 per cent increase in evaporation.

If, as suggested by the statement of Professor Thomas Russell, the wind over the lakes is double that at the shore stations, or say 20 miles per hour over the lake, instead of 10 miles at the datastation, **the computed increase in evaporation due to this excess of wind velocity would be 50 per cent over and above that estimated in preceding tables and diagrams.** But notwithstanding the comparisons at Chicago, by Mr. Hazen in 1882, reported on pages 461 to 463, we are not yet certain about these relative velocities, at all of the Great Lakes, and **so have assumed the velocity at lake surface to be the same as at the Weather Bureau Stations.**

EFFECT OF DIFFERENCES IN HUMIDITY

The humidity over the lakes, or at the shores, also varies from that at the data stations, as is shown by the following diagrams, and to correct for these humidity differences involves far greater difficulty and uncertainty than to correct for wind.

The relation of the respective relative humidities at the two locations does not fully represent the difference in evaporative force, which is more correctly represented by difference in vapor pressures.



COMPARISON OF RELATIVE HUMIDITIES AT DATA STATIONS AND AT WEATHER BUREAU STATIONS AROUND THE GREAT LAKES

The relative humidities, month by month, at the data stations are given in the first of the two diagrams above, and the average relative humidity for each Great Lake is given in the diagram next below.

At the Weather Bureau Stations about the Great Lakes, the relative humidity is found materially larger than at the data stations, due, doubtless, to the proximity of this large body of water, and the winds from off the lake. This tends to lessen the amount of evaporation and thus offsets to an uncertain extent the effect of the greater velocity of the wind.

These differences in condition over the lakes from those at the data stations **plainly call for some method of estimation** that shall take proper account of these differences in condition, **and include factors for wind and humidity,** or rather for the vapor pressure difference between the water and the air over the lake.

The more correct basis of comparing forces producing evaporation at data stations and at each lake is shown in the two full page diagrams that follow, on pages 128 and 139.

These diagrams bring out very plainly the great differences in the primary evaporative force of (V-v), or vapor pressure difference of water and air, over the Great Lakes from those at the data stations.

The first of these diagrams compares the **water** temperature and the **dew-point** temperature, month by month, **at each data station,** with that over each of the Great Lakes.

The forces tending to produce evaporation during the winter are seen to be vastly greater over the open Great Lakes, than at the ice-covered data stations, while in early summer these forces are much smaller over the lakes.

At Lake Superior the best data available on temperature of water surface and dew-point temperature of air indicates that **almost no evaporation occurs from Lake Superior in the early summer months,** but that evaporation is extremely high in winter, and this is fully confirmed by records of lake levels and discharge, and by the negative yield of Lake Superior from mid-December to the middle of March.

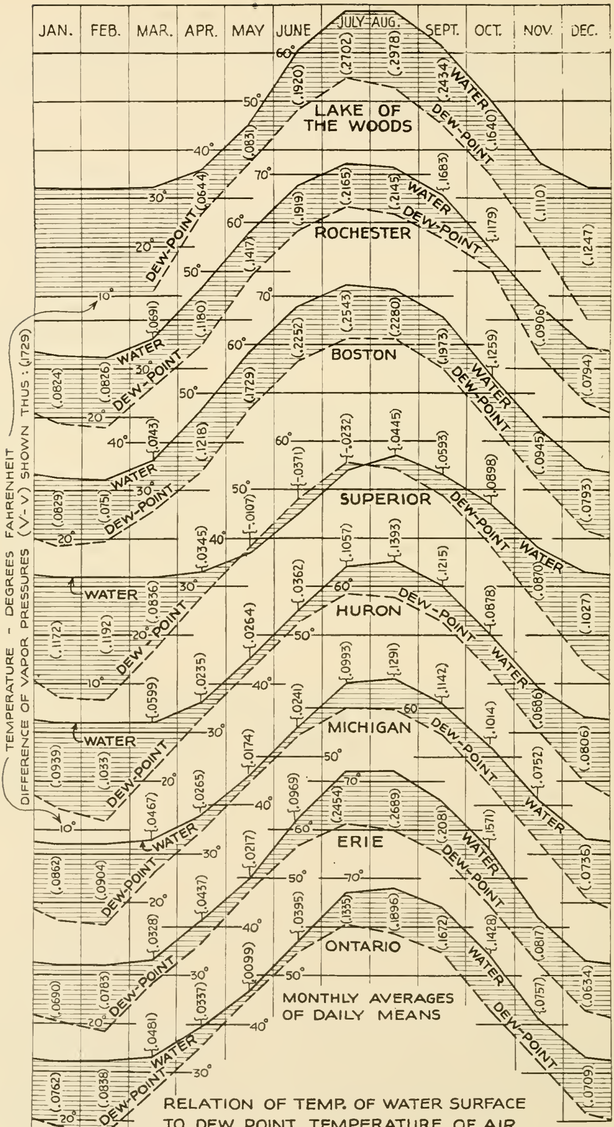
The actual water yield of the lake and its tributaiy land drainage is measured accurately by the gaged outflow and the observed lowering of the lake during the winter months.

Abnormally small yield of the lake as a whole, and even a negative water yield, might conceivably be produced by the large outflow through the St. Marys River being greater than the yield into the lake from the ice-bound streams.

Fortunately there have been sufficient independent measurements of the inflow from these ice-bound tributaries, both in the United States and in Canada, to give a tolerably good determination of the mean depth, month by month, of the winter run-off from the land.

Until these many concurrent data on stream-flow measurements are disproved or the accuracy of the winter gagings of the U. S. Army Engineers are shown to be seriously in error, **there is no escape from the conclusion of large evaporation from Lake Superior in January and very small evaporation from it in May.**

The diagrams on the opposite page lead independently to the same conclusion.



RELATION OF TEMP. OF WATER SURFACE TO DEW POINT TEMPERATURE OF AIR
OR INDEX TO VAPOR PRESSURE FORCES PRODUCING EVAPORATION-(V-v)

THE FOURTH METHOD OF ESTIMATING EVAPORATION

Based on the Dalton Law

A fourth method of estimating evaporation from the Great Lakes, including allowances for effect of water temperature, air temperature, humidity and wind, based on vapor pressures and wind movement was tried out, because it soon became evident that in order to compensate for differences of conditions found in relative temperatures of air and water, and for differences in relative humidity found over the Great Lakes, and in order to extend the application of the only available data beyond the limits of observation at these data stations, **one must have recourse to the physical laws controlling evaporation.**

These laws were discovered and fairly well established by experiment by John Dalton, the great English natural philosopher, about 125 years ago. The approximate accuracy of his deductions is fairly well supported by the experiments of Fitzgerald some 40 years ago, and by others; and Dalton's general theory has never been seriously disputed, although found to need some minor adjustments for obtaining greater precision in its application to estimates.

In attempting to apply the physical laws to estimating evaporation, the writer has been **unable to find any records,** other than those at Boston, Rochester, University of North Dakota and Grand River Lock, Wisconsin, that have been made under climatic conditions similar to those found in England, in New England, or around the Great Lakes, **in which all of the fundamental data were observed with sufficient precision to be directly applied to the estimation of depth of evaporation** directly from the climatic data at the Great Lakes or elsewhere.

The writer also distrusts the application of data on depth of evaporation in relation to temperature derived under very different climatic conditions, from certain experiments made at Denver, and Fort Collins, Colorado, at Reno, Nevada, and in California, and distrusts, as data for present purposes, certain other observations in which relative humidity, or dew-point temperature, was not determined close at hand.

Evaporation from a lake may be regarded as an expression of the excess of the quantity of radiant heat received from the sun and surroundings, over the heat radiated into space, while the water acts as a storage reservoir for thermal units, alternately coming in and going out by radiation. Obviously, **the clarity to heat radiation of the air in California and Colorado averages very different, month by month, from that over the Great Lakes.**

NEED FOR NEW RESEARCHES ON LAWS OF EVAPORATION

It is high time that further research be made with the aid of present-day laboratory resources, of delicate thermometry, of electric heaters, electric fans, electric stirrers, vapor absorbents, air conditioners, refrigerating coils, etc., by which the effect of a **change in one cause at a time** can be measured, and the confusion of causes plainly evident in data now on record, could be eliminated. **It would cost relatively little to provide the necessary outfit** and to conduct first a series of laboratory experiments, and to supplement these by further experiments on large tanks, either on a floating raft or on a rigid base on an island, pier or crib, provided with a stirring device to simulate waves and a small heater to keep the tank from freezing over in air at 30° below zero, and by further comparative observations made on ships and ferry boats navigating these waters, which would include the simpler ordinary Weather Bureau station instruments and an improved Piché evaporimeter. Care must be taken that water in the tank represents that in the lake **in content of ice** and temperature, or to allow for total heat content in Btu.'s per cubic foot.

The data that are being accumulated at many reservoirs in the semi-arid parts of this country, of depth evaporated per week, or per month, from floating tanks, commonly about 3 feet in diameter, **with no accompanying records of wind near water level and no temperatures of air, of water and of dew-point recorded, are of little more than local value, and tell little about the general laws.**

Various algebraic formulas, of greater or less elaboration, have been written for estimating evaporation from temperatures, humidity, wind movement and barometric pressures, but the writer cannot find that those so far published present any advantage over the original simple methods of Dalton, who made use of no algebraic formula, but simply had recourse to the four fundamentals of:

(1) Temperature of water surface,

(2) Dew-point temperature of the air,

(3) Velocity of wind,

(4) A table of saturated vapor pressures, in inches head of mercury, corresponding to temperatures by the Fahrenheit scale.

The future formulas may perhaps contain a heat supply factor and a better vapor diffusion factor, but until some short comings are shown by precise experiments, covering a wide range, the Dalton formula promises the best results.

The Dalton law has an advantage that it can be expressed very simply. It may be written:

$$E = C\ (V\text{-}v)\ (1+KW) \quad \text{or} \quad = (V\text{-}v)\ (C+CKW)$$

In which

E is the evaporation in inches depth per 24 hours.

V is the saturated vapor pressure corresponding to the temperature of the water.

v is the vapor pressure corresponding to the dew-point temperature of the air.

C is a coefficient of evaporation determined from experiment for winds less than 3 miles per hour.

K is a coefficient for wind effect.

W velocity of wind in miles per hour.

The present writer will anticipate the statement of a later page, by stating here that he finds the simple expression

$$E = (V\text{-}v)(0.5+0.05W)$$

expresses the results of all of the experimental data that he has found applicable to these conditions around the Great Lakes.

Elaborations of the simple Dalton formula thus far rest on extremely insecure, unproved foundations.

The researches on which the laws of evaporation rest, have been so few that it seems worth while to describe them briefly, as a reminder that they are few, far between, and incomplete; and that further research is greatly needed for determining the constants in the Dalton formula with greater precision and over wider range, particularly the wind factor, not only for the Great Lakes estimates, but as a guide in many other problems of reservoir yield.

EARLY RESEARCHES

In the interesting bibliography on evaporation published in the *Monthly Weather Review* for June, 1908, it is of interest to note that a century before Dalton's time (in 1693) the great natural philosopher and astronomer, Edmund Halley, had described a year's observation of evaporation at Gresham College, and noted the important effects of open air, exposure and wind; and that in 1747, G. W. Richmann, writing in Latin, gave the results of his experiments showing that evaporation was proportional to difference of temperature of water and air, and was less in shallow vessels, because of lowering of the water temperature by evaporation. In 1756 and 1757 the subject engaged the philosophical attention of Benjamin Franklin. More than a century ago various observers had recorded the annual total depth of evaporation, as for example, 32 inches at Paris, 28 inches at Montmorenci, 28* inches at Utrecht, etc. Evaporation from ice had been measured, and *the condensation of atmospheric moisture observed on water surfaces when these were more than 15 degrees cooler than air at 75 degrees to 87 degrees*: but it remained for the clear vision of John Dalton to formulate the general laws and to do this so accurately that his statement of them is accepted today.

DALTON'S RESEARCHES UPON EVAPORATION

Dalton began his researches on vapor pressures and evaporation about 1801, by first working out experimentally a table of saturated aqueous vapor pressures for different temperatures. He next experimented upon the laws of evaporation, and reasoned from his observations that the quantity evaporated was the resultant, or difference between two opposing forces, the first of which was an outward pressure from the water surface tending to push out particles of vapor with a force equal to that of the vapor pressure corresponding to the temperature of the water; while the opposing force tending to prevent evaporation, could be measured by the pressure of the aqueous vapor existing at that time in the atmosphere.

He developed the standard method for measuring this atmospheric vapor pressure by a determination of the dew-point, or temperature at which condensation of atmospheric moisture began upon the walls of a vessel the temperature of which was slowly lowered.

Based upon this research, Dalton prescribed a simple method of estimating evaporation from a water surface by observing its temperature and taking out from his table of saturated vapor pressures:

(1) The vapor pressure corresponding to the temperature of the water.

(2) Taking out the vapor pressure corresponding to the dew-point temperature of the air, both pressures being measured, then as now, in inches head of mercury.

He found that upon substracting the second from the first, **the difference gave a measure of the rate of evaporation;** which, however, needed some further adjustment to allow for different velocities of air movement at the surfaces in contact.

The development and application of coefficients for use with Dalton's law are described in Appendix No. 2.

*One of the most remarkable facts about evaporation from an open reservoir is that in spite of all of the vicissitudes of heat, cold, wind, humidity, and altitude, the total in the course of a year comes out so nearly alike, year after year, and at localities far apart.

The activity of air currents in the ordinary laboratory or living room, which ordinarily are imperceptible to the senses, can be made apparent by the motion of the motes in a sunbeam, or by a strong beam of light from a projection lantern or by generating light fumes from a small cup containing hydrochloric acid, set in a saucer containing aqua ammonia.

The feeble eddying air currents over an evaporation pan in a closed room, are seen to be of a very different ordei of activity from those presented in a breeze of more than 4 miles an hour, or equal to the monthly average of about 10 miles per hour, shown by the wind gages at the Weather Bureau stations around the lakes.

Two very different kinds of vapor blanket have to be considered:

(1) The small, thin, invisible blanket of elipsoidal form described by Preston, which gathers over the top of a small evaporation pan in a closed room, or in the absence of a strong air current, and retards the escape of vapor, by its partial saturation, by its chill, and by interference with the needed supply of fresh air at the surface films.

(2) The vast invisible high blanket of moisture-laden air over a great lake, sometimes revealed as fog, sometimes as a cloud spreading beyond its borders, but more often a thin haze, or unseen, which affects insolation, or the trapping of heat from the sun, and prevents the loss of heat at night by radiation, each to an important amount.

Probably in most practical out-of-door conditions, or for estimating the depth of evaporation per day or per month from a large reservoir, and particularly from one of the Great Lakes, these factors just mentioned **all will be taken care of automatically in the temperature data observed, and by two or three empirical coefficients with all of the precision and accuracy that the best present data can justify,** without need for recourse to either the theories of thermodynamics, or radiation, or to the kinetic theory of diffusion of gases.

After more of precise and accurate observations, these fundamental physical laws may point the way to a better formula than Dalton's.

FORMATION OF ICE CRYSTALS IN SUSPENSION

Another condition very different from that found heretofore in the laboratory, is found in the open lake, due to its exposure of open water at 32°, kept from freezing by motion from the wind, although exposed to zero air, **while evaporation is going on, perhaps more rapidly than in midsummer,** and is calling continually for heat, to be rendered latent in vaporization in addition to loss of heat by radiation.

On the Great Lakes in winter where the winds prevent the formation of a sheet of ice on the surface, **ice must nevertheless be produced** by this loss of heat, and millions of minute crystals of ice (mostly invisible)must become suspended in the water, in order to release from their latent heat, by solidification, the thermal units necessary to evaporation.

The researches of Professor Howard T. Barnes of Magill University (Ice Formation*, page 181) have shown that these microscopic needle-like crystals, **will not adhere to each other, or agglomerate, unless the water is under-cooled a very few thousandths of a degree below 32 degrees F.**

Doubtless the total quantity of ice thus formed near the surface of the open lake is substantially larger than that comprised in the sheet formed on still water under the same temperature and the same radiation; because when an ice sheet is formed, this serves as a blanket, and lessens the heat lost from contact of the cool air with water at 32 degrees F. The top of the ice sheet may become cooled much below 32 degrees F. and its thickness interposes a non-conductor.

There is a limit to this process of ice-making, set by the quantity of water that can be evaporated, and by the heat received from the sun, so that the total quantity of ice crystals formed in course of the whole winter is not larger than can be maintained in suspension within a few feet of the surface, by vertical rotation set in motion by the wind.

DERIVATION OF CONSTANTS FOR DIFFUSION AND WIND EFFECT IN A FORMULA FOR EVAPORATION

Coefficients are needed in order to adjust the data obtained on evaporation from floating tanks at Boston, Rochester and elsewhere, so as to compensate for the known differences of conditions here from those over the Great Lakes, in:

(1) The greater wind velocity upon the water surface,

(2) The much cooler water temperatures,

(3) The open, ice-free surface in winter,

(4) The possibilities of a different order of vapor blanket.

It is obvious that a formula is necessary for convenience of analysis of observations and data, and that coefficient "C" must be determined for application to the evaporation factor (V-v), for expressing the in-

*Note—This excellent book (published by Wiley & Sons, N. Y.), presents some admirably clear statements regarding the absorption of solar heat by an open water surface, and the loss of heat by radiation into space from a mass of water, and its interception by moisture in the air.

fluences of vapor blanket and the rapidity of escape and diffusion of the vapor from the water surface, and that also a coefficient which we will call "K" must be had, expressing the law of increase in evaporation caused by a given increase in wind.

As stated above, the writer has found no formula which in simple general form, appears more rational than the expression of Dalton's law, (unless it be that of Marvin, not yet tested).

Dalton's Law of Evaporation may be written.

$$E = C(V - v)(1 + KW)$$

in which

E is evaporation in inches depth per 24 hours,

C is a constant governing the rate of evaporation, as affected by diffusion of vapor or by source or rate of heat supply.

K is a coefficient expressing the effect of different wind velocities.

W is the stated mean velocity of the wind, in miles per hour.

To meet the present condition of estimating evaporation from the Great Lakes the formula may be simplified by omitting consideration of variation of the diffusion constant (C) from small dishes with thin metal walls exposed to the air, and for variation in the wind constant (K) for wind velocities of less than four miles per hour, or greater than ten.

In other words, a straight line formula will serve for wind effect, until much more exact data are available.

Formula Used for Method No. 4

After studying pretty much everything that can be found in the standard text books on hydrology, and in many excellent papers in the *Monthly Weather Review*, and in transactions of the Engineering Societies, the writer has been compelled to fall back on the Dalton formula, and to apply coefficients derived chiefly from the Fitzgerald out-of-door experiments, and confirmed to some extent by those at Rochester, and also confirmed by Mr. Fitzgerald's final adjustment of observations upon average depth in inches evaporated month by month in an average year in the Boston district, as related to the observations of the U. S. Weather Bureau and summarized in the diagram on page 103.

For the wind coefficient K, the writer has been governed largely by the slope of the mean lines, on the following diagram, derived from Mr. Fitzgerald's laboratory experiments in an open shed, on dishes one inch deep and 14.85 inches in diameter, as set forth in his table No. 5; but does not accept this series as fully representative of open air conditions, believing that the small size, shallow depth and exposure under a roof, or forces now unknown, may have caused the increase of about 30% in depth evaporated, which this series shows in comparison with open air experiments on floating tanks.

The available data have been plotted in the diagram that follows, so as to exhibit variations in the combined diffusion coefficient and wind coefficient, by regarding the curve of increase as a straight line which intercepts the axis at a point measuring the diffusion coefficient, while its inclination shows the rate of increase corresponding to increases in wind velocity.

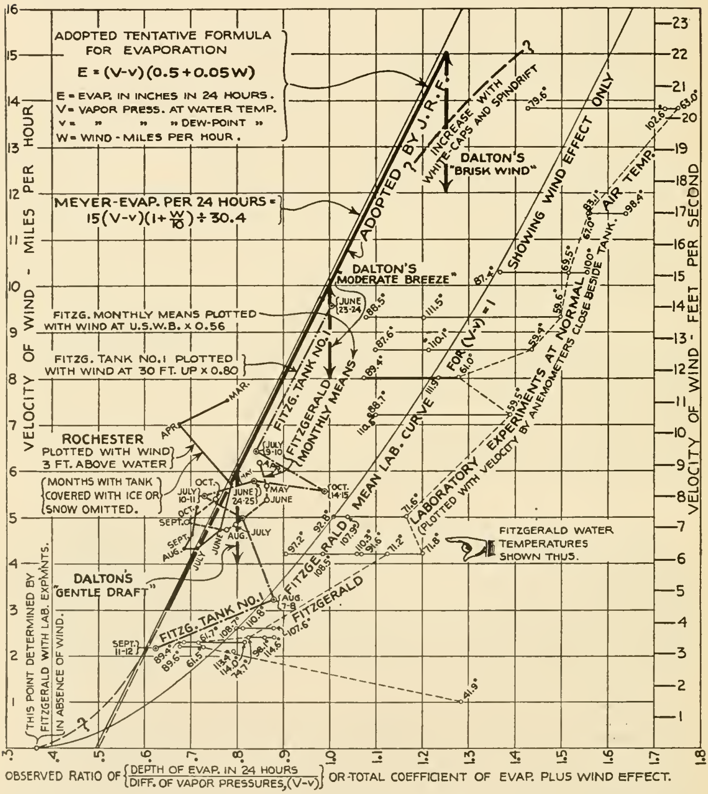
For present purposes, the formula adopted is:

$$E = (V-v)(0.5 + 0.05W)$$

The development of this formula is described in detail in Appendix 2.

After the writer had derived this formula **from these observations** by means described in the appendix, he was much interested to discover its precise agreement with the formula used by Prof. Adolph F. Meyer, in Trans, Am. Soc. C. E., 1915, page 1074, in computing the evaporation at St. Paul, Minn., and at Rochester, N. Y.

Professor Meyer plainly is entitled to priority in the application of these constants. His treatise on Hydrology does not give this formula, but gives this same wind factor as "tentatively" adopted, without explaining how he had derived it.



DATA ON INCREASE OF EVAPORATION DUE WIND VELOCITY.

The determination of coefficients for use in this formula is described further in Appendix No. 2.

The reason for not making use of more of Mr. Fitzgerald's indoor laboratory series is that there are doubts about the diffusion of vapor having been entirely normal, and there is question of abnormal currents in water and air caused by the high temperature of the water baths in which his shallow evaporation dishes were heated.

Moreover, in accordance with the statement previously quoted from Preston, the small diameter of these laboratory evaporation pans tended to higher rate of evaporation per square foot of area than would have been found in pans 3 feet or more in diameter of the type ordinarily immersed in a reservoir.

Estimates of evaporation from each lake have been made as per table on page 140, proceeding on the lines of the Dalton formula, from the data on vapor pressure differences and wind given in the diagram on page 139.

COMPARISON OF RELIABILITY OF THE FOUR METHODS BASED ON METEOROLOGIC DATA

The first method was merely a first approximation, excellent for its purpose but plainly incomplete in its data used.

The second method, although that commonly used where mean air temperatures are available, is plainly incomplete in taking no account of the extraordinary coolness of the lake water, and of the large wind movement over the lakes.

The difference between the fourth method and the third is so great that the writer is not prepared to accept at full face value the figures based upon the vapor pressure method, although he believes them the most reliable of the values by the four methods.

In the absence of continuous observations there are possibilities of error of a very few degrees in the mean values adopted for temperature of the water surface, and large possibility of error in assuming that velocity of wind in mid-lake averages the same as that observed at the Weather Bureau Stations.

It is hard to believe that there is an entire absence of evaporation from Lake Superior in May, June and July, as is estimated by the vapor pressure method by strict adherence to the available data on temperatures of air, water and dew-point, over the mid-lake region, but this is conformed by the hydrographic estimates on page 79.

The observations on opposite sides of the lake at Milwaukee and Grand Haven with wind first in one direction and later in another, illustrate that the data on temperatures and relative humidity obtained from either of the stations on opposite shores do not precisely represent conditions in mid-lake, but indicate that the monthly means in which all station records are averaged can not be far wrong. The probabilities are that the shore air temperatures average perhaps from one to three degrees too low; and because of the fogs it seems probable that the humidity, or dew-point temperature, is higher at mid-lake than by the average of the two values on opposite shores.

The following conclusions are fully warranted in view of the results of the hydrographic method.

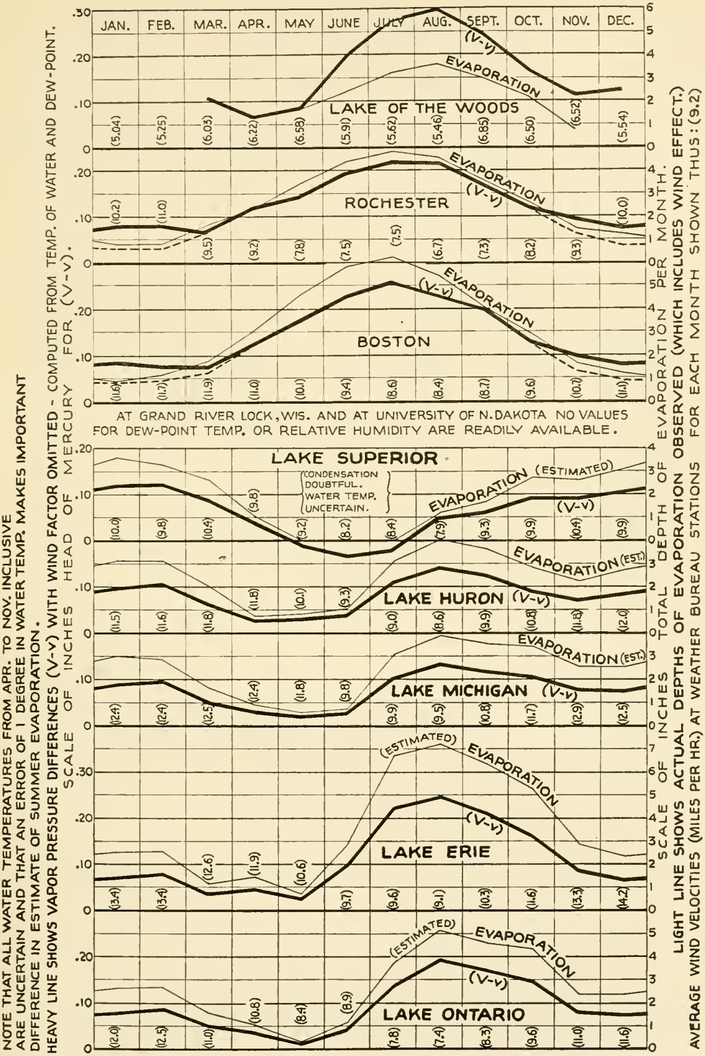
(1) **There can be no doubt that the evaporation in winter from all of the Great Lakes is very much larger than is given by ordinary formulas, or by tables or diagrams based on temperature of air alone.**

(2) There can be no doubt that **in summer the actual evaporation is much less** than indicated by these ordinary methods based on air temperatures alone, because of the coolness of the lake water and the presence of fogs.

(3) There can be no doubt that the third method from water temperatures alone will give more reliable estimates than the second method, from air temperatures alone, or that the fourth method will give more accurate results than the third method.

(4) There can be no doubt that the measurements of evaporation from water surfaces at Boston, Rochester, Lake of the Woods or the other localities of similar temperatures, rainfall, and humidity, from which are available measured monthly depths of evaporation from a water surface, all fail in representing accurately the conditions which chiefly effect evaporation from the Great Lakes until compensation is made for differences in temperatures, vapor pressures, and wind velocities.

(5) That **conditions of insolation by day and of radiation by night,** also of relative humidity applying to observed depths evaporated from water surfaces in Colorado, Nevada, and California differ so greatly from those presented over the Great Lakes as to render data from these localities unsafe for use in the present problems.



RELATION OF EVAPORATION TO VAPOR PRESSURE DIFFERENCE AT DATA STATIONS AND ON GREAT LAKES.

ESTIMATED AVERAGE EVAPORATION FROM THE GREAT LAKES

Inches Depth per Month

Computed from average monthly values of water temperatures, dew-point temperatures and wind velocities, by the following formula:

$$\text{Evaporation per 24 hours} = (V\text{-}v)(0.5+0.05W)$$

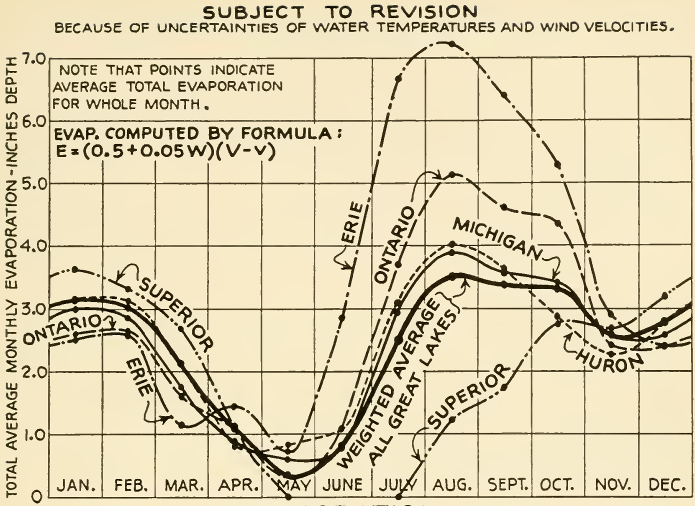
Month	Lake Superior	Lake Huron	Lake Michigan	Lake Erie and St. Clair	Lake Ontario	Weighted Averages Based on Area
January..........	3.63	3.13	3.00	2.50	2.60	3.16
February......	3.30	3.13	2.85	2.56	2.64	3.02
March............	2.65	2.02	1.63	1.15	1.57	2.01
April..............	1.02	0.77	0.89	1.44	1.05	1.05
May................	0	0.82	0.59	0.69	0.28	0.28
June................	0	1.05	0.72	2.86	1.12	0.83
July................	0	3.11	3.06	6.66	3.68	2.50
August............	1.24	4.01	3.90	7.20	5.11	3.50
September.....	1.71	3.62	3.56	6.34	4.59	3.34
October..........	2.77	2.83	3.41	5.26	4.34	3.33
November......	2.66	2.24	2.58	2.85	2.36	2.54
December......	3.17	2.75	2.57	2.37	2.37	2.78
Total Annual	22.15	29.48	28.76	41.88	31.71	28.42

The tabular values given in table above are plotted in the following diagram, giving the computed evaporation month by month for each of the Great Lakes, in a form similar to that on pages 110 and 118, derived from temperatures of air and water respectively. The heavy full line shows the average monthly values for all the Great Lakes weighted according to area.

Below this, for comparison, is given a diagram plotted from the results, on page 79, of the estimated difference between the inflow and the outflow of each lake.

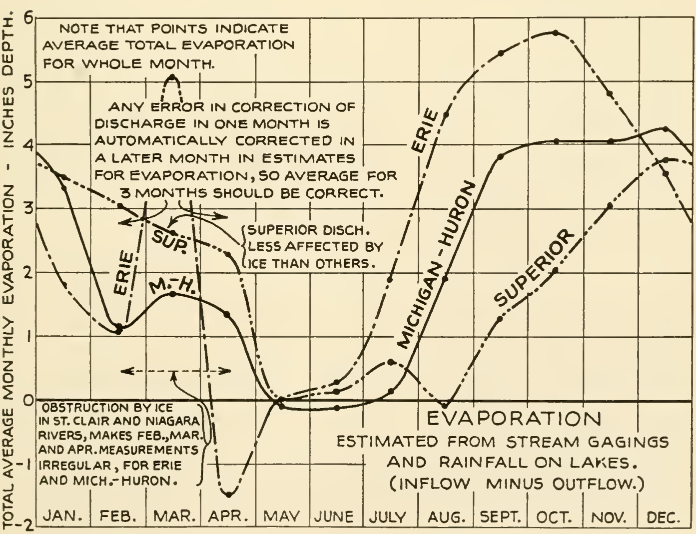
The general form of the curves by these two radically different methods of estimation is seen to be very much the same.

The average values of evaporation in each month found by the five different methods are given in the tables which follow:



EVAPORATION

COMPUTED BY ABOVE FORMULA FROM AVERAGE MONTHLY VALUES OF WATER TEMPERATURES, DEW POINT TEMPERATURES AND WIND VELOCITIES.



MONTHLY EVAPORATION FROM GREAT LAKES (INCHES DEPTH) DETERMINED BY VARIOUS METHODS

	LAKE SUPERIOR					LAKE HURON				MICH. HURON	LAKE MICHIGAN			
	Russell Estimate at U. S. W. B. Stations Piché Basis	Estimated from Diagram of Evaporation and Air Temperature	Estimated from Diagram of Evaporation and Water Temperature	Computed by J. R. F. E=(V-v)(0.5+0.05W)	Estimated from Inflow minus Outflow	Russell Estimate at U. S. W. B. Stations Piché Basis	Estimated from Diagram of Evaporation and Air Temperature	Estimated from Diagram of Evaporation and Water Temperature	Computed by J. R. F. E=(V-v)(0.5+0.05W)	Estimated from Inflow minus Outflow	Russell Estimate at U. S. W. B. Stations Piché Basis	Estimated from Diagram of Evaporation and Air Temperature	Estimated from Diagram of Evaporation and Water Temperature	Computed by J. R. F. E=(V-v)(0.5+0.05W)
January	0.65	1.45	1.62	3.63	3.52	0.65	1.38	1.62	3.13	3.33	0.62	1.37	1.62	3.00
February	0.65	1.46	1.62	3.30	3.07	0.80	1.40	1.62	3.13	1.12	0.87	1.37	1.62	2.85
March	0.75	1.37	1.62	2.65	2.63	1.00	1.42	1.62	2.02	1.66	1.25	1.65	1.65	1.63
April	1.60	2.00	1.65	1.02	2.26	2.10	2.30	1.80	0.77	1.39	2.42	2.52	1.93	0.89
May	2.40	2.90	1.87	0	0.08	2.55	3.25	2.45	0.82	-0.11	2.87	3.50	2.55	0.59
June	2.90	3.82	2.45	0	0.12	3.70	4.20	3.35	1.05	-0.13	4.12	4.49	3.45	0.72
July	3.65	4.42	3.25	0	0.61	4.20	4.82	4.28	3.11	0.17	5.12	5.12	4.50	3.06
August	3.35	3.70	2.90	1.24	-0.06	3.95	4.10	3.80	4.01	1.91	4.25	4.48	3.92	3.90
September	3.05	3.08	2.52	1.71	1.32	3.00	3.45	3.20	3.62	3.83	3.30	3.70	3.30	3.56
October	3.25	2.32	2.12	2.77	2.07	2.35	2.58	2.30	2.83	4.04	2.80	2.78	2.45	3.41
November	1.25	1.52	1.73	2.66	3.06	1.60	1.77	1.78	2.24	4.03	1.95	1.94	1.84	2.58
December	1.15	1.37	1.60	3.17	3.78	0.90	1.38	1.60	2.75	4.24	1.02	1.40	1.60	2.57
Total	23.75	29.41	24.95	22.15	22.46	26.80	32.05	29.42	29.48	25.47	30.65	34.32	30.45	28.76

	LAKE ERIE					LAKE ONTARIO				WEIGHTED AVERAGES ALL 5 LAKES ON BASIS OF AREA			
	Russell Estimate at U. S. W. B. Stations Piché Basis	Estimated from Diagram of Evaporation and Air Temperature	Estimated from Diagram of Evaporation and Water Temperature	Computed by J. R. F. E=(V-v)(0.5+0.05W)	Estimated from Inflow minus Outflow	Russell Estimate at U. S. W. B. Stations Piché Basis	Estimated from Diagram of Evaporation and Air Temperature	Estimated from Diagram of Evaporation and Water Temperature	Computed by J. R. F. E=(V-v)(0.5+0.05W)	Russell Estimate at U. S. W. B. Stations Piché Basis	Estimated from Diagram of Evaporation and Air Temperature	Estimated from Diagram of Evaporation and Water Temperature	Computed by J. R. F. E=(V-v)(0.5+0.05W)
January	0.90	1.39	1.62	2.50	1.80	0.55	1.38	1.62	2.60	0.66	1.37	1.62	3.16
February	1.25	1.38	1.62	2.56	1.06	1.05	1.37	1.62	2.64	0.84	1.39	1.62	3.02
March	1.46	1.88	1.65	1.15	5.06	1.00	1.68	1.65	1.57	1.03	1.43	1.64	2.01
April	2.91	2.72	2.15	1.44	-1.49	2.40	2.56	2.01	1.05	2.12	2.30	1.83	1.05
May	3.65	3.78	2.71	0.69	0.02	3.30	3.55	2.55	0.28	2.76	3.26	2.31	0.28
June	4.48	4.75	4.05	2.86	0.28	4.35	4.45	3.55	1.12	3.67	4.22	3.06	0.83
July	5.48	5.30	5.06	6.66	1.90	4.25	5.12	4.62	3.68	4.38	4.83	4.09	2.50
August	5.31	4.75	4.68	7.20	4.47	4.05	4.42	4.20	5.11	3.98	4.12	3.64	3.50
September	3.60	3.98	3.94	6.34	5.41	3.70	3.76	3.65	4.59	3.21	3.45	3.02	3.34
October	3.05	2.92	2.80	5.26	5.87	2.65	2.80	2.62	4.34	2.56	2.60	2.35	3.33
November	2.16	2.04	1.88	2.85	4.81	2.20	1.95	1.84	2.36	1.67	1.76	1.78	2.54
December	1.35	1.45	1.62	2.37	3.57	1.15	1.42	1.60	2.37	1.08	1.37	1.60	2.78
Total	35.60	36.34	33.78	41.88	32.76	30.65	34.46	31.53	31.71	27.96	32.10	28.56	28.42

CONCLUSION REGARDING DEPTH EVAPORATED FROM THE GREAT LAKES

All of the available data concur in showing that the depth of evaporation over the Great Lakes follows a very different order, from month to month, from that heretofore supposed to prevail over all reservoirs and lakes.

The Great Lakes all give their highest evaporation in the fall or winter and their smallest in the late spring and early summer.

The only two out of the five methods of estimating the evaporation, month by month, in preceding pages, entitled to confidence are:

(1) That found by subtracting the measured inflow from the measured outflow for each lake.

(2) That found by method No. 4, by computation based on the vapor pressure differences of air and water, and the velocity of the wind.

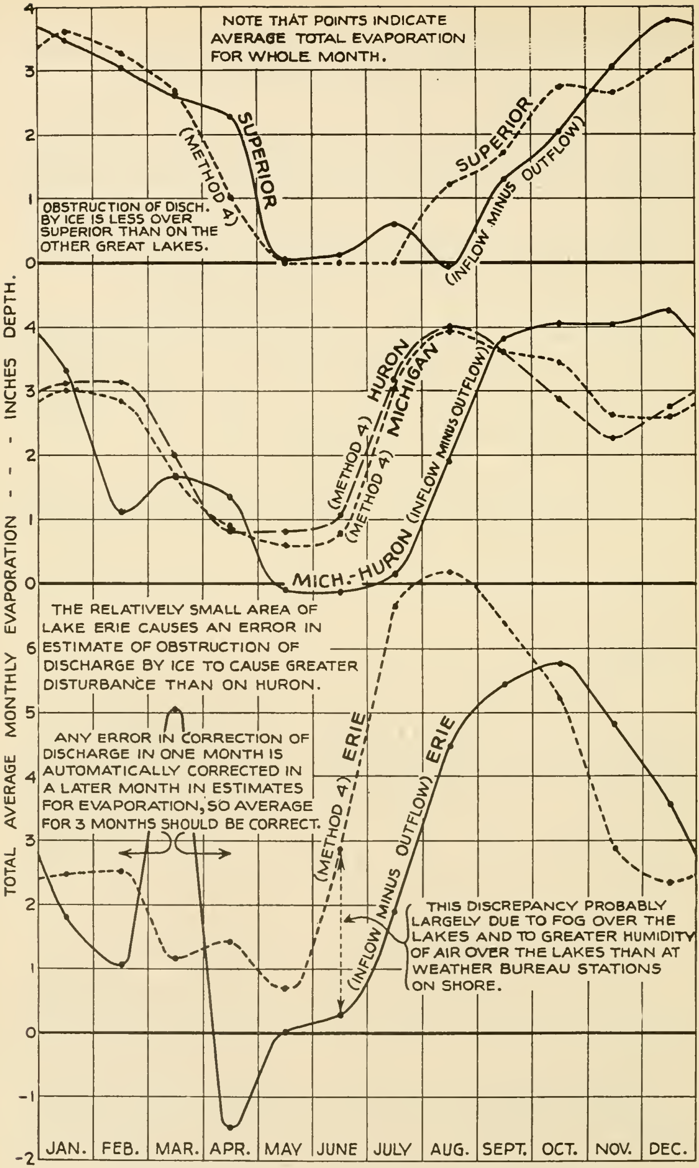
The following diagram has been made up to compare the results obtained by these two methods of estimation.

The general shape of the curve of depths from month to month by these two methods agree remarkably, considering their entire independence in data and method of estimation. The discordance comes chiefly in the curve estimated from temperature, humidity and wind, during the summer, running ahead of that by water gagings by about 1½ months. The evaporation estimated during June, July and August from temperatures, humidity and wind is one to 2 inches larger, perhaps mainly, because of the restraining influence of fog, or because of too low an estimate of humidity in the air, or in other words, too low a figure for the vapor pressure in the air over the lakes.

The uncertainties of data have been explained elsewhere.

The chief element of uncertainty in the hydrographic method seems to lie in the lack of definite information about the effect of ice in obstructing the discharge of the St. Marys, St. Clair and Niagara Rivers.

The chief element of uncertainty in the meteorologic method of estimate probably lies in the temperatures of water and dew-point over the lakes.



COMPARISON OF EVAPORATION ESTIMATES
BY HYDROGRAPHIC AND METEOROLOGIC METHODS.

PROBABLE DEPTHS EVAPORATED, IN INCHES, FROM EACH OF THE GREAT LAKES

There is, at times, need of the best approximation now possible, of the inches depth of evaporation from each of the Great Lakes in an average year, therefore, the following is submitted, subject to revision.

The adopted values differ very slightly from the precise average of the values in the preceding columns, and were adjusted slightly according to the writer's judgment in giving weight to various circumstances.

For Lake Ontario no computation was made to show the loss between inflow and outflow therefore the adopted values for monthly evaporation given below for Ontario are based primarily on the estimate from meteorologic data.

MONTH	SUPERIOR			MICHIGAN—HURON			ERIE			ONTARIO	
	Computed by Formula E=(V−v) (0.5+0.05W)	Inflow minus Outflow (5 years)	Adopted Values	Computed by Formula E=(V−v) (0.5+0.05W)	Inflow minus Outflow (10 years)	Adopted Values	Computed by Formula E=(V−v) (0.5+0.05W)	Inflow minus Outflow (10 years)	Adopted Values	Computed by Formula E=(V−v)(0.5+0.05W)	Adopted Values
Jan.	3.63	3.52	3.5	3.06	3.33	3.0	2.50	1.80	2.4	2.60	2.6
Feb.	3.30	3.07	3.2	2.99	1.12	2.5	2.56	1.06	1.9	2.64	2.1
March	2.65	2.63	2.6	1.82	1.66	1.8	1.15	5.06	1.3	1.57	1.5
April	1.02	2.26	1.5	0.83	1.39	1.0	1.44	-1.49	0.6	1.05	0.8
May	0	0.08	0.1	0.70	-0.11	0.3	0.69	0.02	0.4	0.28	0.4
June	0	0.12	0.1	0.88	-0.13	0.4	2.86	0.28	1.6	1.12	1.0
July	0	0.61	0.3	3.08	0.17	1.6	6.66	1.90	4.0	3.68	3.3
August	1.24	-0.06	0.7	3.96	1.91	3.0	7.20	4.47	5.7	5.11	5.1
Sept.	1.71	1.32	1.5	3.59	3.83	3.7	6.34	5.41	5.8	4.59	5.2
Oct.	2.77	2.07	2.3	3.12	4.04	3.6	5.26	5.87	5.4	4.34	4.5
Nov.	2.66	3.06	2.9	2.41	4.03	3.4	2.85	4.81	3.9	2.36	3.5
Dec.	3.17	3.78	3.3	2.66	4.24	3.2	2.37	3.57	3.0	2.37	3.0
Total	**22.15**	**22.46**	**22.0**	**29.12**	**25.47**	**27.5**	**41.88**	**32.76**	**36.0**	**31.71**	**33.0**

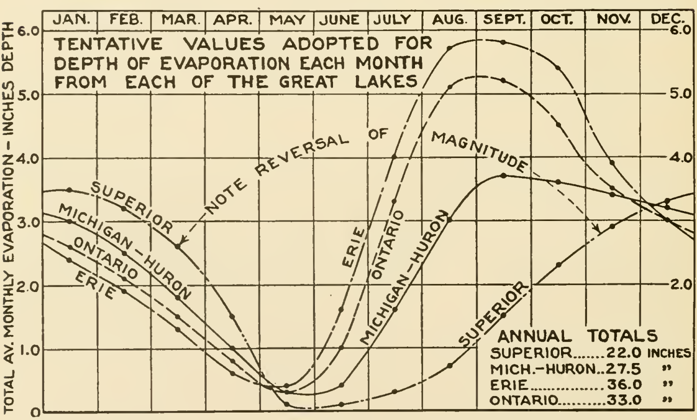
In conclusion, as to these quantities thus found, the writer has been led to accept them by force of cumulative evidence and as the only logical deduction from the best data he has been able to find. The precise quantities, month by month, are tentative and subject to revision.

The data and the line of deduction are presented so that each one who has the interest and patience to follow the matter through may decide for himself.

These results are strongly at variance with what the writer had expected to find but it is deemed important to present them in the hope that both these strange results of evaporation, larger in January than in May or June, and the obvious poverty of observations and the imcompleteness of the purely scientific theory of evaporation, will lead to the making of direct measurements of a high order of accuracy by the Lake Survey, by the Weather Bureau and by the superintendents of Municipal Water Supply at the lake cities, and to scientific study of these phenomena by the great institutions of learning around the Great Lakes.

To some extent this chapter on evaporation is presented as a challenge for someone to produce something better, both in data and in theory.

The adopted values for monthly average depth of evaporation from each of the Great Lakes, as given in heavy figures in the preceding table, have been plotted in the diagram below, which clearly shows the periods of maximum and minimum evaporation.



VARIATION IN EVAPORATION FROM YEAR TO YEAR

The total depth of evaporation possibly varies from year to year nearly as much as the rainfall. Dr. C. F. Marvin, Chief of the U. S. Weather Bureau, has suggested that years of small total rainfall, if this means years of fewer rainy days than ordinary, would probably be years of large evaporation from water surfaces. Obviously, evaporation is smaller during hours of cloudiness and rain than in clear weather.

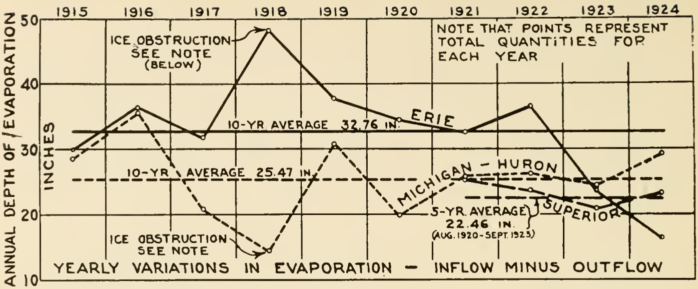
We have little data on this variation, outside the lakes themselves as set forth on pages 65 to 80, except that given by the observations upon the floating tank at the Rochester reservoir since 1891, and that at Keewatin since 1913 and the 6 years of observation on the Boston Water Works. (The 10-foot Boston tank was in service during less than one year.) The annual totals for these as published have been plotted in the diagram that follows, for comparison with the diagrams showing variation in rainfall and in water yield from year to year.

The total annual evaporation from each lake as estimated from the differences between inflow and outflow, are presented in the diagram on top of the following page. These are irregular, largely because of the uncertainty in the correction to be applied to the discharge formulas of the St. Marys, St. Clair and Niagara Rivers, to allow for obstruction of discharge by ice. The diagrams below give data from Boston, Rochester and Keewatin, for comparison.

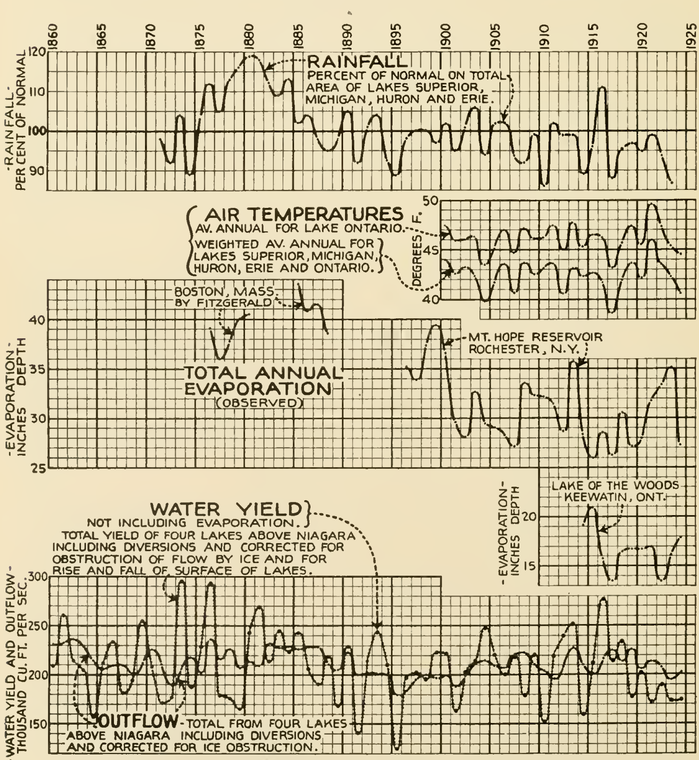
The conditions at these small tanks at Rochester and Keewatin, and at Boston, in exposure to wind and other factors, are far from being representative of those which control evaporation from the Great Lakes. About all that they can show which is useful in the present study, is that at Rochester the evaporation from this small tank varied from 26 inches to 39 inches, in one year as compared with another, which is **a range of 50 per cent increase;** and that at Keewatin, Lake of the Woods, the range in evaporation was from 14 inches to 21 inches, also a **range of 50 per cent increase.**

If anything like so great a variation occurs on the Great Lakes (which can hardly be believed), its application to the enormous quantities of water which go off into the air from the lake surface would cause great changes in lake levels.

The only reliable information on this change in evaporation from year to year must come from a study of inflow and outflow from the Great Lakes themselves, and it was along this line that the late Professor Hayford was intending to attack this problem, from a more exact and substantial foundation than that available to the present writer in his hydrographic studies presented on pages 65 to 80 of the present report.



Note that the uncommonly large ice jams in the St. Clair River in 1918 would increase the differences between inflow and outflow in Lake Erie, causing an apparent excess of evaporation, while the opposite effect would be produced in lakes Michigan and Huron



CLIMATIC VARIATIONS FROM YEAR TO YEAR

TILTING OF THE EARTH IN THE GREAT LAKES REGION

That the surface of the earth throughout the entire region of the Great Lakes has been slowly tilting upward to the north and east during the past fifty years at the rate of from ½ foot to 1 foot per 100 miles per century, has been proved by many comparisons of lake levels throughout his region. The direction of the axis to maximum tilt is about 20 degrees north of west, and the probable position of the "hinge line" is a little south from Cleveland and Chicago.

The hinge for this gentle movement may not be along a sharply defined angle, but along a curve of gently decreasing slope. Its limit probably is 150 or 250 miles southerly from the more definite and more angular hinge line of the greater prehistoric tilting described on page 164 and shown in the section on page 166.

This tilting is revealed by a comparison of the records from gages by which the elevation of water has been measured each day continuously for 50 or more years past, at several places on each of the Great Lakes. Twenty pairs of long-term gages have been used in measuring its amount and direction.

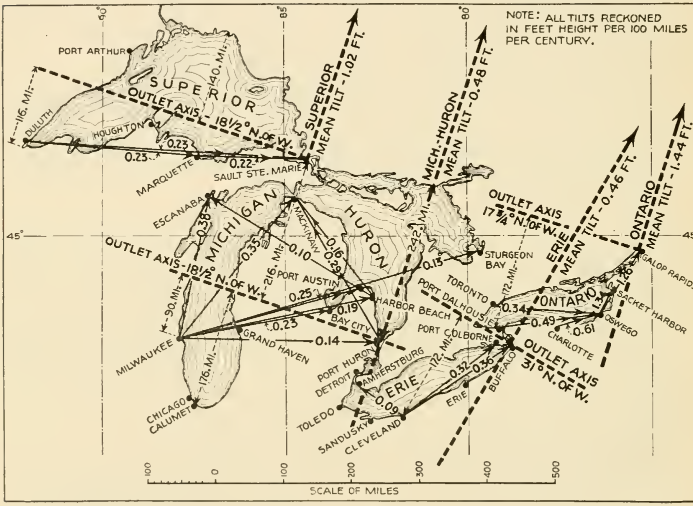
There is, however, a fairly definite "hinge line" for the far greater tilt found to have occurred in prehistoric times. An explanation suggested for all of this movement is that isostatic readjustment is still going on, in the nature of a slow recoil from the depression caused thousands of years ago, by the weight of the great glacier coming down from the north, of which, evidence exists in vast, wide-spread deposits of glacial drift, extending south to within about 100 miles or less frcm the present location of the Ohio River.*

Whatever the cause, **continuous progressive tilting upward toward the north** at the rate of about half a foot per 100 miles per century in the southern part of the Great Lakes region, with indications of double this rate over some parts of the Lake system, **is proved beyond all doubt,** by the comparisons of simultaneous water heights at some 20 pairs of water gage stations at opposite sides, or near opposite ends of the same lake, made continuously throughout each year, for 50 years, as set forth in diagrams that follow.

In the following diagram the amount and direction of the tilt measured at each of the Great Lakes has been worked out separately, from records of the gages by which the lake levels have been measured day by day for 65 years past; but for reasons of precision of measurement some of the earlier less careful records have not been used for this purpose.

*The farthest reach south for the latest, or Wisconsin ice sheet, is marked by the Hartwell marine 10 miles north of Cincinnati, Ohio, and by another at Hillsboro, Ohio, and by one near Columbus, Indiana, some distance south. (See Mr. Leverett's Monograph XLI, U. S. G. S., plate III and page 307.)

In the following diagram, the rate of tilt found in feet height, per 100 miles, per century, between the several pairs of gages, has been marked upon a line joining the gage locations. Also a line called the "outlet axis" has been drawn through the outlet of each lake, parallel to the deduced hinge line. The direction and average rate of tilt for each lake deduced from all of the comparisons is shown by the arrow.



RATES AND DIRECTIONS OF EARTH-TILT FOR EACH OF THE GREAT LAKES

DEDUCED FROM COMPARISONS OF CHANGE IN HEIGHTS OF WATER DURING THE PAST 50 YEARS—SHOWN BY PAIRS OF GAGES AT LOCALITIES SHOWN ON MAP—MAINTAINED BY THE U. S. LAKE SURVEY AND OTHERS

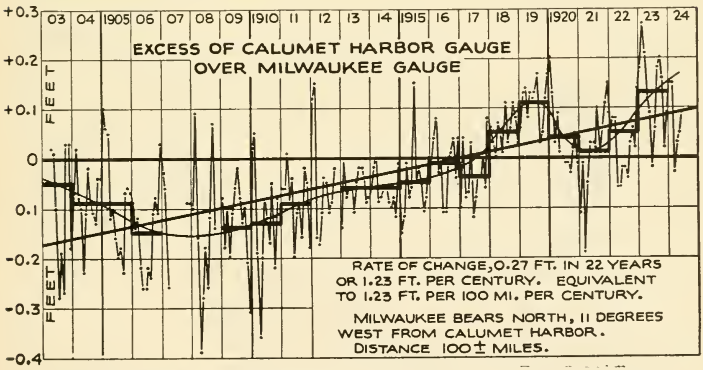
The tilt shown between Milwaukee and Chicago was found at rate of nearly 1.0 ft. per 100 miles per century, and seemed so large that it was not entered above until datum of gage could be verified. This has since been reported correct.

The tilt found by adopting the Calumet instead of the Milwaukee gage is shown in diagram on page 152.

The probable past or future elevation or depression at any point on the margin of the lakes, at any time, obviously can be estimated by measuring its distance at right angles from the outlet axis, and applying the rate of tilt.

Although the determination of the rate of tilt for each lake in the diagram above, is **entirely independent** of those for the other lakes, **all four determinations agree remarkably well.** All slopes point in nearly the same northerly direction and the axes of tilt for all are substantially parallel. The rate of motion for Michigan, Huron and Erie are practically the same, while the slope of the surroundings of the two more northerly lakes, Superior and Ontario, is larger, and thus conforms to an entirely independent line of evidence of prehistoric tilting found in the sloping remains of ancient gravel beaches and lines of wave erosion cut into the base of ancient cliffs, by all of which evidence the slope becomes more steep near the northern limits of the lake region.

The recent comparisons between the gage readings at Calumet and Milwaukee are shown in the diagram below, both for monthly means and yearly means. The departures of the yearly means from the straight line is nowhere greater than 0.083 ft. or one inch, and is probably due to the irregular effects of winds and seiches in disturbing the lake levels, rather than to variations in the rate of tilt. The same is true in greater degree, of the departures of the monthly means from the straight line. The purpose of the studies of the late Professor Hayford on effect of wind upon lake levels, was to reduce or eliminate irregularities of this kind.



COMPARISON OF MONTHLY MEAN GAGE READINGS

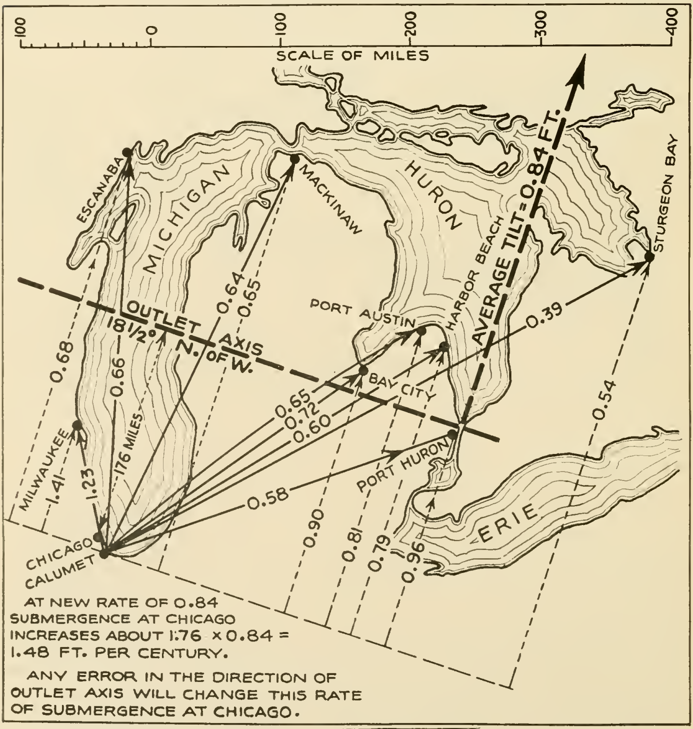
Adjusted to Precise Levels of 1903

This greater rate of tilt shown between Milwaukee and Calumet (now that the Calumet gage has been verified) suggests something anomalous about the Milwaukee gage. Taking Calumet as the focus for lines radiating to Escanaba, Mackinaw, Sturgeon Bay and Harbor Beach, much steeper or more rapid rates of tilt are shown for the Lake Michigan-Huron region, than by the diagram on the preceding page, and this more rapid rate is more nearly in accord with the rate of tilt found by the gages around Lakes Superior and Ontario.

The diagram on the next page shows the result of using the Calumet gage as the point of comparison, instead of the Milwaukee gage.

Continuous water levels, taken with the care and precision that has been used by the engineers of the U. S. Lake Survey for the past 25 years at all of these automatic recording gages about the Great Lakes, **give a more precise and positive determination than can be had by the most careful spirit leveling.** After these gage readings have been reduced to mean lake level by Professor Hayford's methods, this series will give the most precise measure of earth tilt over a wide range of country that is available anywhere in the world.

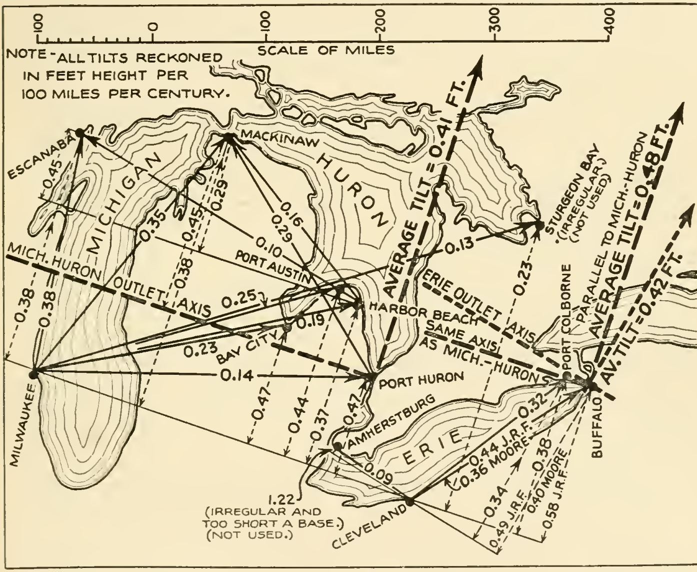
The lines of motion worked out from some 20 different pairs of gage records, with lines running in different directions shown in condensed form above, all show a concordant relation to the mean axis, which is most convincing proof of recent uplift and **leaves no doubt that this motion has been systematic and continuous during the past 50 years.** For how much farther back than 50 years, or how far north it extends, we cannot say, although the ancient shore lines of the larger prehistoric lakes in this region suggest that motion has been



RATES OF EARTH-TILT
ADJUSTED TO CALUMET GAGE INSTEAD OF MILWAUKEE GAGE, AND ASSUMING UNIFORMITY OF TILT BETWEEN STATIONS

going on, spasmodically perhaps, since the retreat of the glacial ice-sheet which covered all this region about 20,000 to 30,000 years ago, and that the movement extends north to Hudson's Bay.

The diagram below comprises the portion of the diagram on page 150 relating to lakes Michigan-Huron and Erie, enlarged and with the addition of the computed rate of tilt for each pair of stations, measured at right angles to the outlet axis. Measured from the Milwaukee gage, arranged for comparison. The values adopted provisionally are a mean of those shown in the two diagrams on pages 152 and 153.



RATES OF EARTH-TILT
CHIEFLY FROM MILWAUKEE GAGE TO OTHERS AS SHOWN—ALSO SAME MEASURED PERPENDICULAR TO OUTLET AXIS

Fifty-years Change in Mean Height of Barometer

Because of it having been suggested by a careful student of matters of this kind, that possibly a climatic change has occurred in the course of which the mean path of storms had changed, and the average barometric pressure relation changed from North to South, a diagram was prepared showing the means of the barometric pressures observed for fifty years at Duluth in comparison with Chicago and at Oswego in comparison with Cleveland.

Duluth and Chicago both showed a very slight increase in barometric pressure, of about 0.003 inch in fifty years, which would give an effect on water levels in the same direction as that found due to earth tilt, and amounting to only about 0.002 feet in height of water in a hundred years.

Between Oswego and Cleveland, the change in barometric pressure was found equivalent to a change in water level, in opposite direction to earth tilt, at the rate of 0.024 foot per 100 miles per century.

Thus this change in water levels shown in the preceding diagrams, cannot be attributed to barometric change but must be due to earth-tilt.

PRACTICAL IMPORTANCE OF INVESTIGATING EARTH-TILT

That this is a matter of much practical importance in designing regulation works that are to serve for a long future, is illustrated by the following examples.

The depth over the lower sill of the oldest locks at the Sault Ste. Marie, probably also the depths in the channel of the St. Mary's River, have become lessened by this tilting within the past 50 years, or since 1875, by the amount of 0.54 foot. And **these depths from mean water surface to lock sills and river bed, if left to natural causes, would probably become another 0.54 foot smaller in the next 50 years.**

This results from the fact that the outlet of Lake Michigan-Huron is controlled at a nearly fixed elevation at Port Huron and Sarnia, while the tilt is going on in relation to an axis extending northwesterly from this outlet at a rate probably intermediate between that shown for Lake Michigan-Huron and that found for Lake Superior.

This amount of shoaling of 0.54 ft. (which is a minimum value), is deduced from the fact that the Soo locks and the St. Marys River lie about 216 miles distant north, 18½ degrees east, from a line drawn through the outlet of Lake Huron parallel to the "hinge line," and from the fact that the rate of tilt found from comparison of records of 7 pairs of gage stations on Lake Michigan and Lake Huron, between Milwaukee, Escanaba and Mackinac and Harbor Beach, etc., is at the rate of 0.48 foot per 100 miles per century.

If tilt is going on at the new rate deduced from using the Calumet gage instead of the Milwaukee gage this will be at the rate of 216 x 0.84 = 1.81 feet per century.

Within the same period of 50 years, from 1875 to 1925, the same cause has tended to deepen the channels in Chicago harbor by about 0.42 foot and **possibly by 0.74 ft. in 50 years**; if estimated from the recent comparison between the Calumet gage and the others. This is estimated from the fact that Chicago lies about 176 miles south from the same line projected from the outlet of Lake Huron, parallel to the hinge line, or in a direction 18½ degrees north of west.

At the rate shown by the Milwaukee comparison, the submergence at Chicago is increasing 0.84 ft. per century, while by the Calumet comparison the depths of water here at the south end of Lake Michigan are increasing at the rate of 1.48 ft. per century.

Progressive subsidence at this relatively rapid rate (if verified), is of great importance in problems of land drainage and in maintenance of sewer outflows around the south end of Lake Michigan, also at Toledo and Sandusky.

The north shore of Georgian Bay lies about 242 miles north, 18½ degrees east, from the outlet of Lake Huron; therefore, accepting the rate of tilting as one-half foot per 100 miles pei century, the depths of **the harbors on the north side of Georgian Bay probably now present an average depth of water 0.60 foot less than that possessed by each of these harbors 50 years ago.**

On Lake Erie the diagram on page 162, made by a continuous comparison from 1887 to 1924 of the lake elevation shown by the gage at Cleveland, with the elevation shown simultaneously by the gage at Buffalo — if the correct adjustment of these gages is granted — can leave no doubt that the depth in the harbor at Cleveland has become about 0.32 foot deeper within the 37 years during which accurate comparisons of gages at Cleveland and Buffalo have been possible; because the line drawn so as to average the mean yearly heights, shows an increase at Cleveland of 0.32 foot during this period of 37 years, which is **at a rate from Buffalo to Cleveland of 0.86 foot per century,** or at the rate of 0.44 foot per 100 miles per century at right angles to the axis. Accurate records of height at Cleveland are available continuously since 1860 or 65 years ago, but at Buffalo the records made prior to 1887 are said to have been accidentally destroyed. Thus the length of this particular comparison of gage heights is limited to 37 years.

Cleveland harbor is probably 1.00 foot deeper today than in 1812 because of earth-tilt. At Sandusky and Toledo the increase in depth has been slightly more than at Cleveland, because these harbors are slightly farther south of the axial line through the outlet from Lake Erie at Buffalo. The records of these gages confirm the observation that certain areas of ground near Sandusky on which hay was cut 100 years ago, have become submerged within the century, for equal stages of lake level.

On Lake Ontario the locations of the only long-term gages now known to be reliable, are not advantageous for the precise measurement of the rate of tilting; these pairs being neither far apart nor lying in the direction of maximum tilt; but as far as the elevations at Charlotte, Oswego and Sacketts Harbor can be made to serve this purpose, these, like the few observations on Lake Superior, show that **rate of tilt increases toward the north.**

These ill-conditioned tilt data for Ontario, show a rate of tilt of 1.44 feet per 100 miles per century, but if the rate here is actually only 1.0 foot per century, the depth in the harbor of Port Dalhousee above the lower sill of the old lock of the Welland Canal has probably become 0.86 foot deeper than 50 years ago. **In Toronto Harbor depths also have probably increased about a foot in 50 years.** In other words, relative to the mean level of the lake, there has been a subsidence of the harbor walls, the wharves, and the harbor bottom. These effects are difficult of precise observation by other means than exact and long continued gage readings, because by the continual oscillations of lake height, that occur from year to year, or month to month, under variations of climate, wind and rain.

On Lake Superior, **probably Duluth and Superior Harbors have become one foot deeper than 50 years ago;** but the gage stations on the American shore of Lake Superior, lie along lines so nearly parallel to the hinge line, that the rate of tilt for Lake Superior, is not yet precisely determined. A rate of 1.02 feet per 100 miles per century is indicated for the Lake Superior region, and doubtless the tilt in this northern region is greater than for Lakes Michigan-Huron or than for Lake Erie.

EXPLANATION OF CHANGE IN FALL FROM LAKE HURON TO LAKE ERIE

This measured slow tilting of the earth, also helps to explain a large part of the change in relative elevation of Lake Huron and Lake Erie. There has been a long controversy over the supposed lowering of Lake Huron, with much difference of opinion about the part caused by dredging the channels for the improvement of navigation and subsequent scour. It has been stated by men of skilled experience and judgment, that this enlargement of the outlet has lowered these lakes fully as much as the diversion of water at Chicago.

The recent determinations, as summarized in the diagrams that follow, prove that this tilting (because the control of outflow from Lake Erie is fixed at Buffalo), has increased the gage height at Cleveland and Amherstberg, which lie about 172 miles south of the axis, by about 0.4 foot within 50 years, and that meanwhile the Harbor Beach gage, located about 60 miles north from the axis drawn through the outlet of Lake Huron, because of the tilting, now reads about 0.15 foot lower than in 1875.

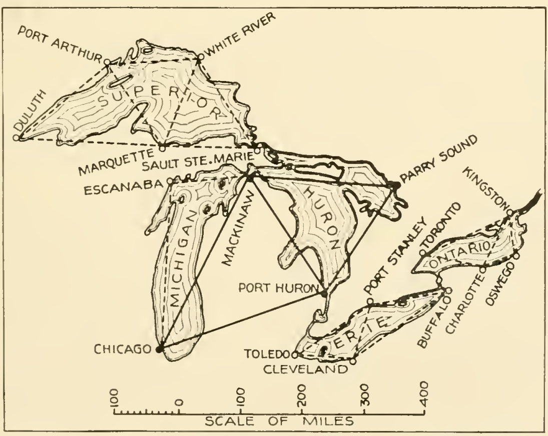
Therefore, so long as dependence in determining the difference in elevation between Lake Huron and Lake Erie is placed on comparisons of readings at the Harbor Beach gage with readings at the Cleveland gage, and not on comparisons of actual water elevations in the two lakes measured **close to the head of the St. Clair River and close to the foot of the Detroit River,** this tilting alone in the 50 years 1875 to 1925 would introduce a gradually increasing error in the apparent drop from lake to lake (making it appear too small in recent years). This error would now amount to about 0.55 foot. In other words, the use of gage readings at the two points named, at elevations determined 50 years ago, would indicate the present drop from Lake Huron to Lake Erie about 0.55 foot less than the actual drop.

(A corollary worthy of attention, is that for measuring the fall through the St. Clair and Detroit Rivers, **the standard gages should be nearer to the lake outlet,** than Harbor Beach and Cleveland.)

A new gage for measuring the height of Lake Huron above its controlling outlet should be most carefully established near the Fort Gratiot Light.

This estimated shoaling of 0.54 foot over the lock sills and in the channels at Sault Ste. Marie, and the apparent subsidence of the lower lock sill at Port Dalhousee by about a foot, and the apparent subsidences of harbor structures at Lewiston and Toronto to the extent of a foot, all within this relatively brief period of 50 years, plainly are of much practical importance; and it is greatly to be regretted that **the appeal made 30 years ago** to the directors of the Lake Survey, and of the U. S. Coast and Geodetic Survey, for establishing well conditioned triangles of gage observation, with longest possible sides, for measuring the progress of this tilting, by the eminent geologist, the late Dr. Grove Karl Gilbert, whose thoughts more often ran in terms of precise engineering measurement than those of most geologists, seems to have fallen on unappreciative ears.

The additional gage stations which Gilbert recommended 30 years ago, should now be established without further delay, and at least two or three others added along the Canadian shores; one on the north side of Lake Superior opposite Marquette; one at Kingston, and one upon the two-mile intake crib of the Chicago water works.



WATER GAGE STATIONS RECOMMENDED FOR OBSERVATION OF EARTH-TILT

Solid lines show those recommended by Dr. Gilbert in 1896.
Dotted lines show others now recommended for the other lakes.

OUTLINE OF RECENT STUDIES

The present writer was led to study this matter of tilting of the earth in relation to lake levels, while seeking explanation of the apparent change in the relative elevation of Lake Huron and Lake Erie discussed on later pages of this report, and by reason of a statement by the late Professor Hayford, repeated on page 133 of his treatise on "Effects of Winds and Barometric Pressure of the Great Lakes," that one of the important problems which he hoped his studies might help solve, was that of the more precise measurement of the tilting of the Great Lakes region toward the southwest, which the late Grove Karl Gilbert had shown by means of a careful study of certain records of water gages from 1876 to 1896, was probably going on at the rate of 0.42 foot per 100 miles per century, with the direction of maximum tilt about 27 degrees east of north.

Inasmuch as this matter of a definite continuous tilting is of great practical importance, and **has not heretofore been taken seriously by the few who have known about it,** it appears important to now go into the matter at length.

THE STUDIES OF DR. GROVE KARL GILBERT

Dr. Gilbert's investigations are described with much detail on pages 595 to 647 of Part II of Report of the U. S. Geological Survey for 1896, under the title "Recent Earth Movements in the Great Lakes Region."

Dr. Gilbert opens his paper by saying:

> "The geologic history of the earth shows there have been great oscillations of level. Modern history also records upward and downward movements of the land at various points. The modern movements are of small amount, but it is believed that they are of the same kind as the ancient, and that the great changes of the geologic past were effected slowly.
>
> "Nearly all discoveries of modern change have been made at the seashore, but there is no reason to suppose that the land is now more stable in the interior of the continents than along their coastal borders."

He proceeds to use the level surfaces of the Great Lakes as datum planes of reference, for measuring the recent rate of tilt, if any, and makes comparison of the gage records of water height maintained daily for many years by the U. S. Lake Survey; carefully selecting for comparison, groups of observations made at times when there was little disturbance by wind. In a few cases he re-established gages observed 20 years before.

On page 601, Dr. Gilbert gives credit to Mr. G. R. Stuntz, a land surveyor of Wisconsin, for first calling attention to evidences observed in 1853 and reported in 1869, that the river beds at the western end of Lake Superior were growing deeper, indicating either a rise in the outlet of the lake, or a subsidence near its western end.

It is said to have long been noticed by geologists and engineers that the mouths of streams entering Lake Superior from the south are sluggish, and that apparently their beds are sinking, while the mouths of streams entering from the north are building deltas and in marked contrast to streams from the south.

On page 603, Gilbert says:

> "In late Pleistocene time, while the great Laurentide ice field, which just before had covered the entire lake basin, was slowly growing less through the melting away of its edges, there were a series of lakes along its southern margin. These were held in at the north by ice, and on other sides by uplands, and they found outlet southward over the lowest passes of the divide between the Laurentian basin and the basins of the Mississippi, Susquehanna and Hudson.
>
> "After the ice had wholly disappeared, . . . Lake Huron, instead of overflowing to Lake Erie, discharged . . . down the Mattewa and Ottawa Rivers to the St. Lawrence."

In deciphering the geologic history of this region much use had previously been made of the shore lines of the ancient lakes. These consist of sand and graveled beaches that once were deltas; of cliffs and strands, carved from the hillsides by the waves. A multitude of these ancient, abandoned shore lines have been traced for great distances by various geologists, and found not level, but sloping upward toward the north, although obviously they **must have been level when formed.** The general direction of rise of all these shore lines is toward the northeast. The amount of inclination has not been everywhere the same. In general, the angle of inclination to the horizontal, measured in feet per mile, shown by the most northerly portions of these old shore lines and accumulated probably through the slow movement during more than ten thousand years, has been a hundred fold greater than the amount of inclination which Dr. Gilbert sought to measure in precise terms of time and space by the direct comparison of water gages within the past 50 years. This northward rising slope of the ancient beaches in many cases inclines more than one foot per mile, and continues for 100 or 200 miles northward, from a hinge line passing through Lake St. Clair and pointing a little to the north of west.

There is no way of determining the rate of uprise of these ancient shore lines in terms of feet lift **per century.** The movement may have gone on at no greater rate than the observed recent change, and may have required tens of thousands of years to accomplish the observed uplift of several hundred feet in the latitude of the Straits of Mackinac; or the increasing steepness may have been more rapid for a time, and slowed down in recent times to the rate now observed.

Dr. Robert Bell has estimated that the land about Hudson Bay and James Bay has risen at the rate of from 5 to 7 feet per century. There is some indication in the gage records that the rate of rise per 100 miles has been more rapid as one goes farther north.

On page 607 of Gilbert's monograph it is stated that:

> "Dr. J. W. Spencer, addressing the American Association for the Advancement of Science in 1894, suggested that **in the far distant future it was probable that continued tilting of the land would ultimately turn the discharge of all of the Great Lakes (above Niagara) into the Mississippi, by way of Chicago,** just as the Huron waters were turned from the Ottawa to the Niagara River in recent geologic time."

The recent studies show this catastrophe is more than a thousand years ahead, and that **for a few hundred years to come, dams and dredging and regulation works, can maintain lake levels where most advantageous to the citizens of the United States and Canada.**

As far back as 1890, Dr. Gilbert suggested to the superintendent of the U. S. Lake Survey, and to the superintendent of the U. S. Coast and Geodetic Survey an investigation to determine if tilting were now going on, and if so, at what rate; but no action was taken. Therefore, he proceeded to himself study the matter from the existing records of lake levels. He selected pairs of gages on each lake as many miles apart as practicable, carefully studied their records of height; and in general selected for comparison groups of simultaneous readings which had been made at times free from abnormal disturbances by wind. He confined his comparisons to gages the elevation of which had been verified at intervals by levels to reliable bench marks, and gave much attention to this matter of permanence, or precise readjustment of the datum of each gage. His **methods were those of an engineer skilled in precision of measurement.**

In general, his early pairs of sets of gage readings had an interval of only about 20 years, from 1874 and 1876 to 1896; but for Lake Erie his pairs of readings for Cleveland and Port Colburn were found dating from 1858 to 1895. Through his extreme care he obtained measurements of rate and direction of tilt which agree very closely with those now obtained from 30 years of additional accumulation of data.

For determining the direction of hinge lines and isobases shown on page 640 of his report, Dr. Gilbert, because of his fewer pairs of gages and his short time interval of 20 years, seems to have been forced largely to rely for direction upon the larger movements and inclinations shown by the shore lines of the ancient lakes, instead of deducing his directions of axes as has now been done, solely from the differences found in pairs of gage elevations; but however determined, his directions concur fairly well with the latest determinations.

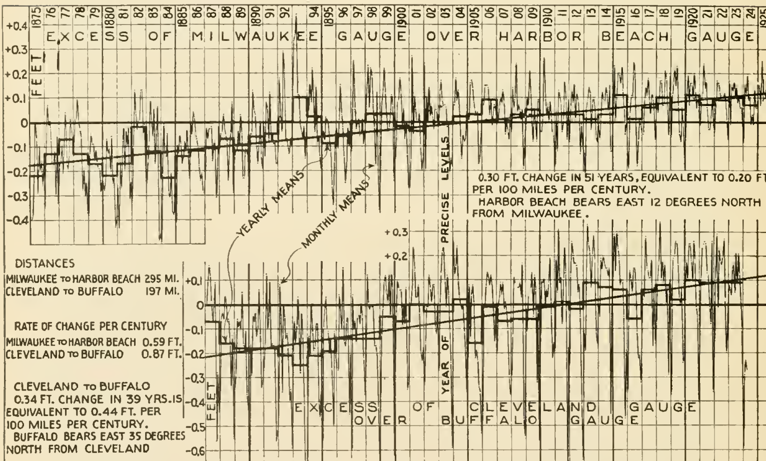
In concluding his paper, Dr. Gilbert quotes from observations reported in 1897, by E. L. Mosely of Sandusky, Ohio, which seemed independently to prove subsidence of one or more feet around the western end of Lake Erie within historic time. These comprised a description of a tract of land, now under water, on which hay was made in 1828, also stumps and prostrate tree trunks lying on ground that is now from one to four feet below the normal lake level; and other facts, all indicating either a rise in the outlet of Lake Erie, or a subsidence of the ground around the southwest end of the lake.

Dr. Gilbert, on page 642, proposes the system of triangulations mentioned above, for further study of the tilting, to be based on future gage readings made at Chicago, Mackinac, Port Huron and Parry Sound, at stations so placed as to give the longest possible base lines for determining both the direction of the hinge line and the amount of the movement. He prescribed the type of gage, the kind of observation, the selection of periods free from disturbances by wind and barometric differences, and the proper referencing of each gage to permanent bench marks. Unfortunately, this excellent suggestion seems never to have been acted upon.

It may be of interest in showing progress in geophysics since the time of Dr. Gilbert's study, that he did not invoke isostacy, or resilience from weight of the glacial ice cap, to explain this tilting.

Additional Studies

Prior to a study of Dr. Gilbert's monograph the writer had compared the two series of gage readings shown in the diagram below, and was much interested to find how closely the rate of tilting shown by this comparison concurred with that worked out independently from different stations by Dr. Gilbert, and reported by Professor Hayford.



COMPARISON OF MONTHLY MEAN GAUGE READINGS
ADJUSTED TO PRECISE LEVELS OF 1903

It is interesting to see that this continuous record **indicates continuous movement at a uniform rate,** and that the frequent divergencies in monthly means and in yearly means, from the straight line in this diagram, are of the order of the aberrations which Professor Hayford hoped to eliminate by means of his studies of effects of winds and barometric waves.*

*Since some, familiar with the effect of seasonal winds upon certain of the lake gages, have thought Dr. Gilbert may have been deceived by these seasonal differences because of the brevity of his observations, particular attention is called to the fact that the record in the above diagram **is continuous both by monthly averages and by yearly averages, and does not admit of this objection,** and therefore is superior to Gilbert's method of selecting only a very few days free from wind.

The preceding diagram presents two separate determinations of the rate of tilting, made originally with reference to finding explanation of the lessened drop from Lake Huron to Lake Erie. Each is independent of the earlier determinations by Dr. Gilbert and of the later determinations by Mr. Sherman Moore, but they are found to be in agreement with both, and with each other.

The zig-zag line in the upper diagram, which is for Lakes Huron and Michigan, connects all of the average monthly differences found by subtracting the monthly average gage readings, corrected to precise levels of 1903, recorded at Harbor Beach, from those at Milwaukee.

The step-lines show the differences found by subtracting the annual averages. The inclined line drawn by the eye to average the yearly averages, gives the amount and rate of the tilt within this period, in the direction of a line joining the two gage locations.

The lower diagram, which is for Lake Erie, was made in the same manner.

Dr. Gilbert's method was to carefully select a period of a few weeks or months near each end of the term, when the level of the lake surface was not disturbed by wind or barometric wave, and omit other and intermediate observations. The writer was desirous of locating time of change, if any, and so **included all reliable observations from beginning to end.**

No evidence of a sudden change is found.

Dr. Hayford's studies, previously referred to, had for one object the smoothing out of the line of aberrations of the zig-zags and of the steps. Although these aberrations are rather wide in places, they are not generally simultaneous in the two lakes, and the determination of constancy, and uniform rate of the motion, appears reliable.

Action at a constant rate also is indicated by the more numerous comparisons by Mr. Sherman Moore.

The more recent studies by Mr. Moore, and by the present writer, **all indicate uniform, continuous movement,** and nothing of spasmodic change as suggested by Mr. Taylor.

After studying Dr. Gilbert's monograph the writer conferred with the Director of the U. S. Geological Survey and with the Chief of the Geodetic Division of the Coast Survey, to learn of later researches, and was referred to the monographs by Mr. Frank Leverett and Mr. Frank

B. Taylor, published by the U. S. Geological Survey in 1915, which deal with the geologic history of the Great Lakes Region. That by Mr. Leverett is mainly devoted to tracing out the limits of the glacial drift and the borders of the ancient deeper lakes that covered sites around the southern parts of Lakes Michigan, Huron and Erie.

FIELD STUDIES BY FRANK B. TAYLOR

The monographs by Mr. Taylor comprise many studies around the southern shores of the Great Lakes, of ancient beach lines and their inclination. Sections are worked out and combined on vertical planes parallel to the shore lines, which clearly bring out the rate of inclination and show that in northern Michigan and Wisconsin, these ancient beach lines, which must have originally been level, began their upward tilt not far from a hinge line passing through the present location of Lake St. Clair, with a trend about 20 degrees north of west. Several tentative hinge-line locations were worked out from slopes at different ancient shore lines.

Near their northern extremities these sections show the inclined ancient shore lines rising from 50 to 300 feet in various localities.

When the ancient lakes were dammed at the north by ice, their discharge was forced over divides to the south, wherefore these ancient prehistoric lake surfaces were at higher elevation than the present lakes, and many of these ancient shore lines are several miles back from the present lake.

A combination of these various profiles shows everywhere a maximum uplift in a direction a little east of north, with isobases parallel to the hinge line already mentioned, extending about 20 degrees north of west from Lake St. Clair, and other points shown on the accompanying sketch. Mr. Taylor states, on page 319 of his monograph:

"This particular history is spread like an open book upon the surface of the lake region," and that it is plain, that in one of the earlier stages, the ice sheet of the glacial age covered the entire region of the Great Lakes with the exception of a relatively small area chiefly in Southern Wisconsin. This vast glacier at its maximum, reached southerly to Cairo in Illinois, and to Beaver Falls in Pennsylvania.

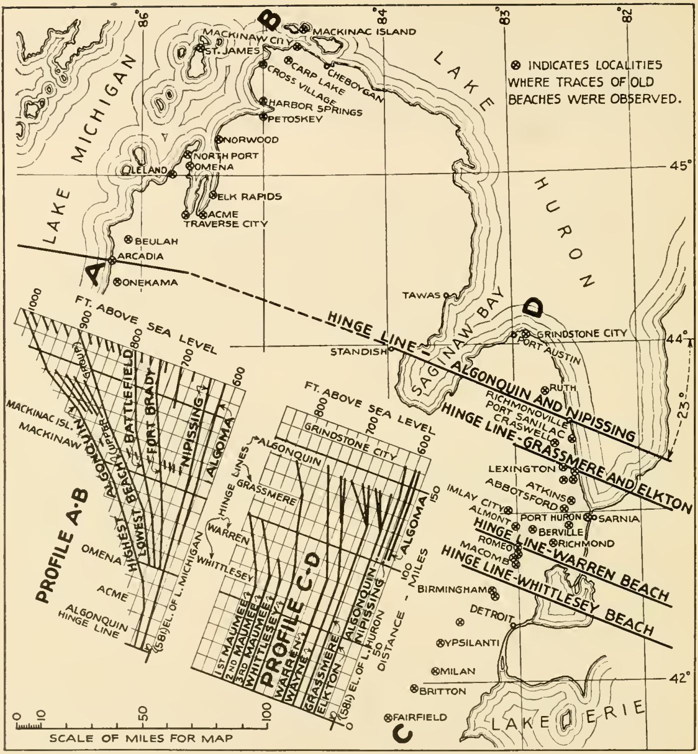
As this ice sheet, by melting, retreated northward it developed lakes along the southern extremities of the present system, deeper and covering a broader area than the present lakes, and discharging to the southwest. It is along the higher margins of these ancient lakes that the inclination of the ancient beach lines is now chiefly measured.

Although Mr. Taylor was familiar with Dr. Gilbert's investigations of the tilting shown by the water level gages he appears to have been more impressed by these earlier evidences of tilting on a far larger scale, and to have believed the inclination resulted from a series of spasmodic movements, and at the time of writing his report (1909), doubted if any movement was now taking place. From later evidence, he now concurs with Gilbert, as to continuity of movement within recent years.

This opinion at variance with Dr. Gilbert's may have been reached because Mr. Taylor's methods dealt mainly with observations of a different order of magnitude from those studied by Gilbert. Taylor studied uplifts of hundreds of feet while Gilbert was dealing with differences in level of tenths of one foot, and it is not strange that the more precise methods of Gilbert and Moore push the location of the beginning of the warping farther south than the hinge lines mapped by Taylor, Hobbs and others, who measured with scales having graduations 1,000 times larger.

Nevertheless, Mr. Taylor's detailed working out of the ancient shore lines, their inclinations, and the probable position of their hinge lines, all are of profound interest, as showing how vast has been this uplift, for perhaps 500 miles in width, along the northern parts of the Great Lakes region, that has been accomplished in the untold thousands of years since the glacial age.

Mr. Taylor's working out of the geologic history of the formation and early pathways of the St. Clair and Detroit Rivers, also is an extremely valuable contribution to the engineering data of this region.



TILT SHOWN BY SLOPE OF ANCIENT BEACH LINES

Prepared from Reports by Frank B. Taylor
Vol. LIII Monographs U. S. Geological Survey 1915, pp. 290–518

The above map transcribed from various maps and descriptions from Mr. Taylor's study of uplift shows the location in a general way of some of the more important ancient shore lines upon which he and others have measured the change in inclination from the close of the ice age to the present time. This map also shows the position of the several hinge lines, as worked out from the inclination of the ancient shore lines, in each of several different regions. The profile below shows the rate of the tilt accumulated in prehistoric times.

The general belief now current among geologists seems to be that the cause of this movement is a slow return of the deep earth mass toward an equilibrium that existed prior to the depression of this northerly region under the great weight of the ice cap of the glacial age; which may have been a mile in thickness along the northern end of the lakes, and retreated very slowly, by melting, probably more than 20,000 years ago.

Such movements of the earth surface, sinking under a great weight and rising when this weight is removed, concur well with the modern theory of isostacy, or gravitational equilibrium; according to which the earth mass beneath mountains has a smaller specific gravity, or smaller weight per cubic mile than beneath the oceans and broad low valleys; and so now generally stands in equilibrium; but wherever equilibrium has not been completed, is slowly and continuously seeking readjustment.

Readjustments of elevation and of position, probably are slowly going on in many parts of the world where weights are being changed by erosion, or deep deposits of sediment, or other cause.

Recent studies of the rate of transmission of the elastic waves that accompany earthquakes and pass through the earth, have indicated that the core of the earth for more than 95% of its diameter, or to within perhaps 40 or possibly 80 miles of the surface, is hard and elastic as a sphere of steel; this hardness being due possibly to the enormous pressure from the weight above.

Isostacy assumes that outside this rigid core, somewhere, about 50 or 75 miles beneath the surface of the earth, there is a viscous layer, some miles in thickness, within which the readjustment toward equilibrium can take place with extreme slowness.

After studying Mr. Taylor's monograph, and noting his doubts about recent movement, the writer next sought to test the theory of Dr. Gilbert about present-day tilting of the earth's surface in the Great Lakes region by means of all of the accumulated gage records of the past 50 years, which obviously give a much longer and better base line than was available to Dr. Gilbert.

Moreover, in 1903, since Gilbert's time, a new line of precise levels was completed all around past the southern limits of the Great Lakes, starting from New York Harbor and proceeding down the Mississippi Valley, checking again with sea level near New Orleans; to which all the gage readings, and recent reports had been corrected. It was sought to extend the determination of tilt, as derived in the diagram on page 93, to all other available long term records about the Great Lakes: but the writer soon found this had already been done in the U. S. Lake Survey office.

Other observations which have been made along the ancient beach lines of the eastern half of Lake Erie basin, on the west side of Lake Michigan, and on the east side of Lake Huron, from which profiles similar to those above have been drawn, show the tilt to have occurred in nearly the same direction, and along about the same hinge lines.

Note that the tilts shown above, are of a far greater order of magnitude, than the tilt shown by progressive gage differences, but are all in the same general direction.

Recent Investigations by U. S. Lake Survey

On taking up this matter of tilting of earth surface with the Lake Survey Office of the U. S. Engineers at Detroit, in the search for additional gage readings, the present writer found that this matter had been the subject of a recent study by Assistant Engineer Sherman Moore, who had published the results of his comparisons in the Military Engineer of May and June, 1922, with additional concurrent data. The Lake Survey Office has provided the writer with additional gage readings, down to the present time, in several of the series used by Mr. Moore.

It now appears that the rate and direction of tilting is not everywhere precisely the same, although nearly so.

Nearly all of these data, old and new, point conclusively to the rate of **tilt of the regions around Lakes Michigan, Huron and Erie being half or three-quarters of a foot per 100 miles per century,** and that its downward direction is 20 degrees west of south, with its axis 20 degrees north of west.

The main hinge lines of the earlier larger movement are about as shown on the preceding map, but the limit of the recent movement with which the evidence of the gages now deals, probably is south of the most southerly limits of the Lakes.

It is interesting to find that although this recent measurement of amount and direction of tilting by Mr. Moore so closely agrees with the determination by Mr. Gilbert, made 30 years earlier, **it was the result of a wholly independent study, using entirely different gage readings.** Mr. Gilbert's gage readings were taken mostly in 1876 to 1896. The period within which all gages used by Mr. Moore were observed was subsequent to 1899.

Mr. Moore states (page 153) that his investigations were prompted by the discovery in the winter of 1919–20, that the levels of Lake Erie at Port Colborne, at the entrance to the Welland Canal, were between 0.10 and 0.20 foot lower than the corresponding levels at Cleveland, although the two had been carefully set to the same datum by water levels in 1875.

On comparing the Cleveland readings with those at Buffalo, it was found that although these had agreed in 1902, Buffalo in 1918 was showing levels about 0.10 foot below the Cleveland readings, showing a lowering of the gage support at Cleveland, although Cleveland and Amherstberg gages continued in agreement. Further investigation proved that the gage at Harbor Beach was showing lower levels than at Milwaukee, and that the Marquette gage was showing lower levels than the gage at Duluth.

The fact that **gages to the north and east in every case were showing lower readings,** was significant and eliminated the possibility of unstable bench marks. Mr. Moore says, "The only logical conclusion appeared to be that there was in progress, a movement of the earth's crust over the entire region, a tilting movement that was causing a relative rise in the land to the north and east."

Also he notes that "the traces of ancient lake beaches may be followed from the west end of Lake Erie where they are only a few feet above the lake to the northerly shores of Lake Superior where they are several hundred feet high. . . . The existence of drowned river valleys on the southern shores of the lakes, particularly Lake Superior, and their absence on the northern shore, confirms the evidence of the beaches."

Regarding the accuracy of determination of old lake heights by gages, Mr. Moore says, "Altho there were records as far back as 1819, they are scattering, were not referred to stable bench marks and are of no practical value for this particular purpose, and that although since 1860 the records are complete at some points, the gages until about 1872, were poorly cared for and were not referenced to fixed bench marks. In the seventies more care was given to the gages and levels were run to them from bench marks at frequent intervals. During the period, 1880 to 1899, the gages apparently received but little care, and at points where there existed unstable conditions the records have little value. **Since 1899, gages have been well cared for, self-registering instruments have been installed and frequent check levels have been run.**"

Mr. Moore took care to pick out reliable gage records from the accumulated mass of data, at widely separated points, covering long periods of time.

For purposes of comparison, Mr. Moore took five summer months, June to October inclusive, as most free from disturbances. Differences between all possible pairs of gages were then taken out, plotted on cross-section paper, and a line drawn by the eye through the observations, to determine the probable rate of change. Distances north and south, and east and west between each pair of gages were measured on the map, and rates of change in each direction worked out. Three pairs were thus used on Lake Superior, nine on Michigan-Huron, three on Erie, and four on Ontario. A least square solution of the 19 equations gave for the north-south component 0.386 foot rise per 100 miles per century, for the east-west component 0.184 foot rise per 100 miles per century, and for the resultant, a tilt of 0.43 foot per 100 miles per century, and the direction 25.5° north of west. The residuals indicated that the tilting was not uniform over the entire area, but the data were insufficient for satisfactory separation into districts with different tilt. It appeared that the tilt was larger for Lake Superior than for Michigan-Huron, and assuming the same direction of axis as for Lake Michigan-Huron, the rate appeared to be 0.94 foot per 100 miles, per century.

A solution of 3 equations for Lake Erie gave 0.46 foot per 100 miles per 100 years; 4 equations for Lake Ontario gave 1.44 feet per 100 miles, per 100 years. Angle of axis for, Erie 31° north of west; for Ontario, 17° north of west.

In conclusion, Mr. Moore states:

"The investigation seems to establish definitely that the crust of **the earth is still tilting in the same direction as it has since the formation of the old beaches,** that the present axis of the tilt is approximately 20 degrees north of west, **that the general rate for the past 50 years has been about 6 inches per 100 miles in 100 years.** It indicates that the rate is not uniform over the entire region, but is about twice as great in the Superior Basins and three times as great in the Ontario Basins as in the remainder of the region."

From all of the data now at hand the present writer has constructed the diagram on page 150, utilizing 20 pairs of gage comparisons. Doubtless a review of lines of precise levels south of the lakes would add information that would more precisely locate the hinge line.

Mr. Frank B. Taylor, in correspondence with the present writer, has suggested that in further studies of tilting by means of gage comparisons, it is important to locate the position of the hinge line, south of which no movement is taking place. If, for example, in the southern part of the region south of a line drawn through Lake St. Clair at 20° north of west, no motion is taking place, then it follows that the rate of tilt is more rapid than has been estimated.

Possibly a retracing of lines of precise levels will determine this, or spurs of precise levels can be run southerly off the main east-west line for this special purpose. New and carefully adjusted gage comparisons after a term of say 20 years between Chicago, Milwaukee and Grand Haven, with other comparisons between Cleveland, Sandusky and Amherstburg also might determine this.

Mr. Frank B. Taylor has reviewed the proof of this chapter on earth-tilt, and in letters dated February 5, and February 17, 1926, states that the "hinge lines" indicated by the inclination of some of these ancient beaches can certainly be determined within from three to five miles, and that with more levels and measurements they could be located perhaps within one mile; that some of the so-called hinge lines, especially those of the Algonquin and Nipissing Beaches (lakes that had no outlets) are in reality nodal lines, or lines where beach planes and water planes intersect. But the data are such, in each case, as to compel us to believe there is a real hinge line, located very near to the nodal line.

The hinges of the earlier beaches are simple hinge lines, not complicated by nodal lines. The Maumee Beach rises northward only 10 feet in 110 miles, which was so slight by comparison, that this was called "within the area of horizontality."

Mr. Taylor expresses regret that there was not space allowed in the publication of the monographs by Mr. Leverett and himself, in which they could give fuller theoretical and interpretative discussions of the facts which they found, and record other important facts.

Mr. Taylor now, 17 years since pages 467 and 468 in his monograph No. 3 were written, states that he regards as unfortunate his statement that the movements of uplift are mainly spasmodic with long periods of rest between, and that he is now very strongly of the opinion that the whole phenomenon is mainly due to elastic distortion and recovery, and that no magmatic movements are involved.

He still finds a few evidences of spasmodic movement in prehistoric times, notably in the Battlefield and Algonquin Beaches, both in the northern part of the lake region. He believes there is clear proof that the rate of uplift has been widely different in different stages. For example, during the making of the compact series of the upper Algonquin beaches, the rate was very slow; then from these beaches down to the Nipissing Beach it was so rapid that scarcely any beaches were made. Only the Battlefield Beach, in the midst of this interval, was notable for strength and continuity.

He considers it highly important to take account of the Algonquin-Nipissing hinge line and of the area or comparative horizontality that stretches southward for an indefinite distance.

The hinge line of the most rapid prehistoric tilting (post-Nipissing) possesses the greatest interest, because the present tilting is quite likely to be simply a continuation of that movement. Taking account of the information since Mr. Gilbert's time, (at the time of Mr. Gilbert's study the hinge line had not been definitely located), the ancient hinge line appears to Mr. Taylor, to run at 5° north of west, across Lake Michigan, but in crossing Lake Huron it passes about west 22 degrees north (monograph 53). Thus, he believes the ancient hinge line curves in crossing the southern peninsula, which introduces a complication in computing the rise on the Milwaukee and Port Austin line, according to where the hinge line is located.

Mr. Taylor states that he and his associates found it difficult to locate the hinge line on the ancient beaches of the Lake Michigan basin as precisely as upon the shores of Lake Huron, but concluded it crossed at 6 miles north of Kewaunee, running about 6° north of west from Acadia on the east shore.

The greater part of the line from Cleveland to Port Colborne possibly lies within what Mr. Taylor had formerly called the "area of horizontality," or south of the hinge of the greater prehistoric movement.

Estimation of the tilt around Lake Erie is more difficult, because neither the Algonquin nor Nipissing beaches extend to that basin. By projecting eastward, the hinge line found in the State of Michigan, it crosses the eastern part of Lake Erie about 21 miles southwest of Port Colborne.

In the Ontario basin, all of the gage stations are surely north of the hinge line, which should make the problem of the rate of tilt more simple if only a sufficiently long range can be had between stations.

Mr. Taylor regards it as highly important that the hinge line of the recent changes be located with all practicable precision and taken account of, as making an angle in the rate of tilt.

He states that it is extremely desirable that gages be carefully established and observed at the mouth of French River, on the northern shore of Georgian Bay, and at Peninsula Harbor, on the northeast corner of Lake Superior.

The following note is from a former chief of the State of Michigan's Geological Survey, who, years ago, was greatly interested in these problems, and to whom the proof of this chapter was submitted.

Tufts College, Mass.
February 11, 1926

The tilting of the old beaches of the Great Lakes is or may be due to four factors:

First: The direct attraction of the ice mass on the water, affecting the level as computed by R.S. Woodward (U.S.G.S. Bulletin 48 and Monograph 1.421–426).

Second: The direct effect of the ice load in compression of the strata underneath. As Woodward once wrote me, if the atmosphere were double, the radius of the solid earth would be shortened two meters.

These two factors would change immediately as the ice front changed. They would be adjusted to the ice front wherever it was. I take it that they largely account for the feathering out of the beach lines to the North and that neglect of them has affected some of the estimates of hinge lines. I think that in your figure, some of the upper beach lines have been extrapolated further north than they go.

Third: The bending down of the crust of the earth into that weak layer, which cannot remain at rest in a state of strain, and is some 30 to 60 km. down, will be slow, depending on the viscosity of the layer. The recovery will be slow also and may still be going on.

To the above factors, I referred, on pages 100–101 of my 1907 report to the Michigan Board of Geological Survey.

Another line of minor effects were not mentioned; that is, the similar effects produced by changes in the water level, as well as the ice.

As I saw last summer, there seems to be a marked four foot drop of lake level all around Georgian Bay. If there was complete isostacy before, there would now be a slight negative anomaly of gravity, and a tendency of the unloaded crust to rise. Since the last ice age there has been a lowering of water level of 200 feet, or so, which would imply a tendency of the crust to rise a substantial amount and certainly accelerate a tilting that already existed. See also Annual Report, Michigan Geological Survey 1905, page 364–369 and Michigan Miner, Vol. II.

Alfred C. Lane

EFFECT OF EARTH-TILT ON DISCHARGE

An examination of the diagrams of earth-tilt on page 150 shows that all of the area of Lake Ontario and all that of Lake Erie lie southerly from the outlet axis. Therefore the effect of raising the outlet must have been to slowly diminish the discharge of lakes Erie and Ontario by reason of the increased volume of water held back within the lake.

In the case of Lake Superior and of Huron-Michigan, the outlet axis crosses the lake system so as to present a larger area to the north of the axis than south of it, wherefore the earth-tilt has slightly diminished the content of each lake and slightly increased their rates of discharge.

By computing the quantities in these wedge shaped volumes accumulated in a half century, assuming the rate of tilt has been uniform at the large rate of 1.0 foot per century per 100 miles and distributing it over the years and seconds, the effects shown in the following table would have been found. They are insignificant in amount.

Lake	Increase in Discharge	Decrease in Discharge
Superior	55 c.f.s.	—
Michigan-Huron	303 c.f.s.	—
Erie	—	96 c.f.s.
Ontario	—	72 c.f.s.

INCREASE IN ELEVATION OF LAKE OUTLETS

Assuming that the hinge line of tilting for this entire Great Lakes region is located about 100 miles south of Chicago, (see page 149), and runs at an angle of about 18 degrees north of west, and that the rate of tilt over the whole region has been going on at the rate of 0.60 foot per 100 miles per century, then the outlets of the different lakes have been raised above sea level during the past 65 years, or from 1860 to 1924, by the following amounts:

	For 65 years since 1860	For 22 years since 1903
Lake Superior outlet	1.91 ft.	0.65 ft.
Lake Huron outlet	1.07 ft.	0.36 ft.
Lake Erie outlet	1.29 ft.	0.44 ft.
Lake Ontario outlet	2.03 ft.	0.69 ft.

The change since the precise levels of 1903, or 22 years by proportion, assuming movement at a uniform rate is about ⅓ of the amounts given above for 65 years, for each lake outlet.

On the above basis the change from Buffalo to Sault Ste. Marie along the line of precise levels would have been about 0.21 ft. in 22 years, which is a difference almost beyond detection by the most precise spirit-leveling in the distance of about 600 miles along the most direct route following the shores of the lakes.

The maximum error allowed in check levels by the Coast Survey is equal to 0.04 ft. x $\sqrt{\text{distance in miles}}$; or for this distance of 600 miles, would be about 0.98 ft.

RELATION OF CHICAGO DIVERSION TO PRESENT PROBLEMS

The diversion of water from Lake Michigan at Chicago through the Sanitary Canal into the Illinois and Mississippi Rivers began about twenty-five years ago and has been gradually increased from an average of 2,990 cu. ft. per sec. in 1920, to an average of 9,465 cu. ft. per sec. in 1924.

Amounts Diverted by Chicago Canal

The average amounts actually withdrawn from Lake Michigan by the Chicago Sanitary Canal as measured at Lockport, are reported by the Engineer of the Sanitary District to have been as follows:

Year	C. F. S.	Year	C. F. S.	Year	C. F. S.	Year	C. F. S.	Year	C. F. S.
1900	2,990	1905	4,480	1910	6,833	1915	7,738	1920	8,346
1901	4,046	1906	4,473	1911	6,896	1916	8,200	1921	8,355
1902	4,302	1907	5,116	1912	6,938	1917	8,726	1922	8,858
1903	4,971	1908	6,443	1913	7,839	1918	8,826	1923	8,348
1904	4,793	1909	6,495	1914	7,815	1919	8,595	1924	9,465
5 yr. av.	4,220		5,401		7,264		8,417		8,674

Average for whole 25 years .... 6,795 c.f.s.

Other Diversions

It may be well to note here that there have been other diversions which have lowered the lakes, the total effects of which will be more than compensated for by the proposed regulating works. For example, the Welland Canal is reported to have taken out of Lake Erie at Port Colborne for some years past about 4,465 cu. ft. sec.; which quantity is larger than the original diversion at Chicago, and is of about half its present magnitude. **This Welland diversion lowers Lake Erie** and all of the adjacent navigation channels and harbors **to nearly half the extent of the present enlarged Chicago diversion.**

About 3,600 cu. ft. per sec. of this Welland Canal diversion is now used for water power development at or near St. Catherine, Merritton and Thorold in Canada; very much as the Chicago diversion is used for power at Lockport (see Warren Report, page 197, also 373).

The old and the new Erie Canals each have diverted about 1000 cu. ft. sec. The flow into the old Erie Canal has been stopped and sections along its upper reaches have been filled with earth.

The old Michigan and Illinois Canal (which was the predecessor of the present Chicago Canal), the Erie Canal and the Welland Canal, had, all three, been diverting more or less water since 1848, or for nearly a half century before there was thought of any interest, public or private, being damaged by such diversions, (see Warren Report, pages 118 and 173).

Until the marvellous developments of electrical power of the past twenty years, and the recent visions of greater future development of hydro-electric power, there seemed to be plenty of water in the Great Lakes for every practical use, and questions of improvement related wholly to lake levels or elevations, or to depths for navigation and to flowage around the shores, and not at all to quantity flowing in the Niagara and St. Lawrence Rivers.

The quantities normally diverted, and their final effect, after a series of years of draft, in lowering the lakes, as estimated by the U. S. Army Engineers, are given in the following table. All of these lowerings of the Great Lakes by diversions **would be compensated for about five times over, by the works now proposed.**

The recent lowering caused by climatic influences is far greater than all of the lowering of lakes caused by the water taken away by the Chicago Canal, the Welland Canal, the Erie Canal and the Power Canals.

The present problem is to find, not merely a remedy for lowerings caused by low rainfall, high evaporation, ice gorges and by the abstraction of water by Chicago, Welland, Erie and Power Canals, but also **to find the largest extent to which lake levels can be safely raised, while their discharge is also regulated,** and the means by which the injurious irregularities in depth and discharge, due **both to climatic influences** and to **diversions** can be overcome, to the greatest extent practicable.

Since the total lowering of lake levels by climatic and other causes for which a remedy is to be sought, is about five times as great as the lowering caused by the Chicago diversion it happens that the quantity of water diverted from Lake Michigan at Chicago does not affect the designs now presented.

In other words, the designs for regulation work in the Niagara and St. Clair Rivers presented in the present report would not be changed in any important part if the Chicago Diversion were cut to one-half its present amount, or if it were to be doubled.

LOWERING CAUSED BY DIVERSION

The precise amount by which the elevation of either of the Great Lakes will be lowered by the abstraction of a definite quantity of water, stated in cubic feet per second, as for example the 4,167 c.f.s. or 10,000 c.f.s. taken out from Lake Michigan by the Chicago Canal, or the 4,465 c.f.s. taken out from Lake Erie by the Welland Canal, can be estimated with certainty by means of diagrams like those shown on page 30, which are deduced from the discharge measurements described on page 29, as will be made plain later in this report.

The data in the following table are condensed from pages 23 and 372 and 375 of the "Warren Report." These were figured for the diversion of 1918 which is not far from that in each of the past 10 years.

Diversion	Amount Diverted cu. ft. per second	Lowerings of Lakes Michigan and Huron at Mean Stage Feet	Lowering of Lake St. Clair at Mean Stage Feet	Lowering of Lake Erie at Mean Stage Feet	Lowerings of Niagara River Chippawa at Mean Stage Feet	Lowerings of Lake Ontario at Mean Stage Feet	Lowering of St. Lawrence River at Lock No. 25 at Mean Stage Feet
Chicago Drainage Canal	8,800	0.43	0.35	0.41	0.23	0.42	* 0.62
Welland Canal	4,500	.03	.09	.21	0.12	....	....
Black Rock Ship Canal	700	....	.01	.03	....	....	....
New York State Barge Canal	1,000	....	....	.01	0.03	....	....
Niagara Power Companies	50,885	.01	.05	.10	0.60	....	....
Total Lowering		.47	.50	.76	.98	.42	.62

*This lowering at Lock 21 amounting to 0.62 has been far more than offset by the rise of about 2.0 feet in this part of the St. Lawrence caused by building the dam across the head of the South Sault, just below the intake of the Aluminum Co's Canal.

These amounts of lowering of lake levels (at most six inches for Michigan and Huron and nine inches for Lake Erie) caused by all of the present diversions all are small in comparison with the raising of water surface in each of Lakes Michigan, Huron and Erie, of from 2 feet to 4 feet which has been found to be possible by means of the regulation works proposed in the present report.

The lowering caused by various rates of diversion at Chicago is estimated as follows:

Diversion at Chicago	Lowering in Feet at Mean Stages				
	Michigan-Huron	St. Clair	Erie	Ontario	St. Lawrence at Lock 25
2,000	0.10	0.08	0.09	0.09	0.14
4,000	.20	.16	.18	.19	.28
6,000	.30	.24	.28	.28	.42
8,000	.40	.32	.37	.38	.57
10,000	.50	.40	.48	.48	.71
12,000	.60	.48	.55	.57	.85
14,000	.70	.56	.65	.67	1.00

REGULATION WORKS vs. COMPENSATION WORKS

The Regulation Works herein proposed, comprising restraining gates and sluiceways, are in substitution for the structures heretofore proposed in the Warren Report and in various earlier reports, comprising submerged weirs in the Niagara and St. Clair Rivers for raising lake levels to the extent of compensating for the drop of about 5 inches caused by the Chicago Diversion.

In nearly all previous proposals for controlling the elevation or discharge of the Great Lakes **improvement of navigation has been almost the only consideration,** with little or no regard to the possibility of storage of surplus water from seasons of uncommonly large rainfall for use in time of drought for benefitting both navigation and power, and in many of these former plans the design has been limited to works only sufficient to slightly more than compensate for this lowering caused by the diversion through the Sanitary Canal at Chicago. In other words previous projects **have sought to raise the lake levels about one-half foot, whereas the works now proposed will raise them an average amount of two and a half feet, or five times as much.**

The investigations ordered by Congress and described in the Warren Report originally contemplated only compensation, not regulation. The authorization is found in Resolution No. 8, Sixty-fifth Congress; continuing in effect Resolution 45 of the Sixty-fourth Congress approved January 19, 1917; According to the words of the resolution, the investigation was to pertain to "The entire subject of water diversion from the Great Lakes and the Niagara River and the preservation of the scenic beauty of Niagara Falls and the Rapids of Niagara River."

While the wording of this resolution covered by implication the design of compensation works for remedying the injurious effects of these diversions, neither its language, nor its small appropriation of $25,000, could be expected to take in the larger horizon beyond the words of the resolution, and contemplated by the present investigation, which comprises designs for:

(1) Raising all these Great Lakes to the highest possible levels.

(2) Regulating all of the Great Lakes so as to provide storage for the utmost future development of water power on the Niagara and St. Lawrence Rivers.

(3) Providing for greater depths of water in channels all the way down from Duluth and Port Arthur, in anticipation of deeper waterways between the Great Lakes and the Atlantic Ocean, so far as practicable to be obtained by increased height of water, with a minimum of expense for dredging.

Nevertheless, the Board on Rivers and Harbors, in reporting in August 1920, did give a limited consideration to this matter of future deeper waterways, in connection with the general improvements at Niagara Falls; which led them to recommend regulating gates at the outlet of Lake Erie, notwithstanding Congress at that time, 8 years ago, evidently **contemplated only compensation works for restoration of elevation lost and not works for the best possible conservation and regulation of the levels and discharges of all of the Great Lakes for all useful purposes;** which is the purpose of the present study.

Assistant Engineer W. S. Richmond, on page 377 of the Warren Report, discusses remedial works of three kinds for **restoring the losses of depth caused by the diversions,** comprising:

(1) Dredging all channels and harbors.

(2) Regulating works for raising lake levels and holding them within fixed limits.

(3) Contraction of lake outlets, raising the lake levels by submerged weirs, without greatly affecting their natural fluctuations.

Mr. Richmond concluded that the first was too expensive. The International Deep Waterways Commission in 1907 had estimated the cost of deepening sufficient to compensate for the diversion of 10,000 c.f.s. at Chicago, as $12,500,000; which would be largely increased by present day unit prices, or probably doubled.

As to the second method, he recalled the proposal of the Deep Waterways Board of 1900 to regulate Lake Erie by gates and sluices and submerged weirs at the head of the Niagara River, by which the lake was to be raised 3 feet above low water, and held within 0.6 ft. of this extreme height, and noted that this was shown, in House Document 779, impossible without also providing for regulating the discharge from the other lakes, but states, "It is quite possible that regulation will ultimately be resorted to."

Mr. Richmond concluded that of the three methods tabulated above, the third was best; and remarks that, "It is perfectly feasible to raise the surface of any of the lakes without interfering appreciably with its natural fluctuations or its average monthly flow." He recommends raising the levels of the lakes by means of submerged weirs in their outlets, having crests 25 feet below low water and estimates that Lakes Huron and Michigan could be raised sufficiently to compensate for the Chicago diversion (see Warren Report, page 384) by a series of 11 submerged weirs containing 250,000 cu. yds. of stone, located in the upper part of the St. Clair River below the outlet of Black River, about ⅓ mile apart, at a cost probably not exceeding $1,500,000. He recommends experiments on models as a means of finding the best design, and that the building of the weirs proceed in an experimental way.

For restoration of loss of elevation in Lake Erie and in the Niagara River down as far as the lower limits of the Chippawa Pool, Mr. Richmond (see Warren Report, page 381) proposed raising the level of the Chippawa Pool 2.41 feet by a low submerged dam or weir, located above the first cascade. This submerged dam to cross the Niagara River from below the Chippawa Creek northerly to within 1,500 feet of Port Day, thence turning downstream to the head of Goat Island.

Since this rise of 2.41 ft. in the Chippawa Pool would cause a rise of only 0.41 feet in Lake Erie, where the total lowering by present and prospective diversions may amount to 1.27 feet, Mr. Richmond proposed that the additional rise of 0.86 ft. desired in Lake Erie be obtained by means of 5 submerged weirs to be built across the head of Niagara River abreast of Squaw Island, some upstream and some downstream from the International Bridge. The weirs as designed contained 185,000 cu. yds. of rock and it was estimated they would cost about $2,000,000.

For compensation works at the outlet Lake of Ontario, it was noted that the Gut Dam already had raised the lake level and that a further rise could be obtained by a narrowing of the American Channel, near the Gut Dam.

On page 382 of the Warren Report, Mr. Richmond notes that the raising of Lake Erie to the extent proposed by means of a submerged weir across the head of the Niagara River, in addition to the rise of 0.42 ft. in Erie caused by the weirs to be built for raising the Chippawa Pool, would leave 0.28 ft. of additional compensation required in Lake St. Clair to fully compensate for the Chicago diversion.

Mr. Richmond directs attention to the fact that this dredged channel through Lake St. Clair is the locality that now presents the most shallow part of the channel between Duluth and Buffalo, and limits depth of draft in transportation. He estimates this deepening of Lake St. Clair probably could be best secured by additional dredging, at a cost of about $160,000.

Colonel Warren concurred in the recommendations of Assistant Engineer Richmond.

Everywhere, the works studied and proposed and recommended by Engineer Richmond and Colonel Warren **were only for compensating for diversions and not for regulation.**

There are some curious contradictions in the conclusions of the several Boards and Committees and individual experts that have discussed the regulation of Lake Erie by a dam at its outlet during the past 25 years, which can be explained by the changing view points and will be considered on a later page.

The U.S. Army Board of Engineers for Rivers and Harbors, in 1919, took a broader view than Mr. Richmond, or Colonel Warren; both of whom apparently had felt action circumscribed by the words of the resolution of congress. These broader views were prompted by the recently proposed regulation of Lake Ontario for the combined use of power development and the creation of a 25 foot or 30 foot channel through the Saint Lawrence.

The Board of Engineers for Rivers and Harbors explains that since the time of making the studies, designs and reports of Mr. Richmond and Colonel Warren "there has been a very marked development of public sentiment in favor of opening the upper St. Lawrence to larger vessels and it seems fairly certain that any such plan will include works for regulating the discharge and level of Lake Ontario. One important objection to restoring the levels of Lake Erie and the waters above it by an adjustable or regulating dam will therefore be removed."

Thereupon, the Board (page 46, Warren Report) **recommended regulation works, extending entirely across the head of the Niagara River,** comprising stoney gates, and states that such a regulating dam at the foot of Lake Erie would have a number of important advantages over the plan of Mr. Richmond and Colonel Warren, such as

(1) Holding Lake Erie at a more nearly uniform level, between elevations 573 and 574,

(2) Increasing low water depths on that lake by 1.5 ft. or more, and

(3) Making the discharge of the Niagara River more uniform or holding it between 180,000 and 200,000 c.f.s. instead of having it sometimes drop to 165,000 c.f.s., as happens for brief periods under present conditions.

They estimated that this dam at the outlet of Lake Erie, with its gates and sluices would cost about $8,000,000.

The U. S. Army Board of Engineers for Rivers and Harbors continued and approved the recommendations of Mr. Richmond and Col. Warren for submerged weirs in the St. Clair River, for the purpose of compensating for the lowering of Lakes Huron and Michigan, due to the diversion at Chicago; and in addition to raising Lake Erie by the proposed dam, they recommended dredging for deepening the channel through Lake St. Clair.

The whole program as recommended by the Board of Engineers for Rivers and Harbors, including works for the preservation of Niagara Falls, recommended by Lieut. Jones, estimated to cost $6,000,000 and which will be discussed later, would thus cost approximately:

(1)	Works for Preservation of Niagara Falls	$6,000,000
(2)	Works at Outlet of Lake Erie	8,000,000
(3)	Dredging Channel in Lake St. Clair	160,000
(4)	Series of Submerged Weirs in St. Clair River	1,500,000
	Total	$15,660,000

It is presumed that the cost of the submerged diversion weir across Chippawa Pool proposed by Lieut. Jones, for diverting more water over the American Fall, is included in his estimate of $6,000,000 for preservation of Niagara.

The need for the series of submerged weirs, recommended by Mr. Richmond, at the outlet of Lake Erie, estimated to cost $2,000,000, would cease with the construction of the proposed dam at the outlet of the lake.

Under the plan of the Board on Rivers and Harbors, after all of this expenditure of about $15,660,000, **Lakes Michigan and Huron would stand at their previous natural levels, subject to climatic fluctuations, and without fully utilizing their vast areas for storage and increase of flow in years following a severe shortage of rainfall.**

BROADER SCOPE OF IMPROVEMENT

As a result of its preliminary studies made in October 1924, this committee on Lake Levels comprising six members of the Engineering Board of Review, deemed it better to give wider scope to its studies than by confining them to determining the precise effect of the Chicago Diversion and to merely devising a complete remedy for the lowering of lake levels caused by the Chicago Diversion. Its members all heartily concurred in the recommendation of the Board of Engineers for Rivers and Harbors as to the desirability of a dam and sluices for the regulation of Lake Erie.

The members of the committee on Lake Levels concluded unanimously that they could render a much more valuable service to the entire Great Lakes Region by considering the control and regulation of the discharges, and thereby the levels of all the Great Lakes, by means of sluiceways, gates and appurtenant structures, in the outlets of Lakes Huron and Erie, in addition to the present structures in the outlet of Lake Superior, and those proposed in the outlet of Lake Ontario.

They recommended that **in the beginning works be built suitable for regulating to the highest possible levels at some future time,** while for the immediate future the levels of the several lakes could be maintained at whatever stages and elevations might be found best for the public interest of both the United States and Canada; having due regard for all of the several uses of navigation, water power development, and scenic effect; in the near future and in the distant future.

The committee found that this broader treatment would be productive of great benefits to navigation in the immediate future and in the more distant future, that it could be made of great benefit to power development, and that it could be made a most effective means toward the immediate repair and preservation of Niagara Falls from their gradual self-desctruction by erosion in the deep notch of the Horse Shoe Fall, which is progressing at the rate of about 6 or 7 feet upstream per year, and which if unchecked may eventually deprive the American Niagara Fall of its water supply.

Concerning this improvement of conditions at Niagara Falls, more will be said later.

IMMEDIATELY BUILDING FULL SIZE FOR FUTURE

Obviously it is better to now take time to consider the demands of the future in relation to power development, to now review the changing economic balance between navigation and water power, and to now design regulating structures of such character and completeness that although their full use may be long deferred, their increased capacity will be available whenever needed, like the 30 ft. future depth now being provided for in the Locks of the new Welland Canal while the new Welland Canal itself is being dug for only 25 feet draft in its early years.

It is found to add relatively little to the total cost, to so design the regulating gates and sluiceways, which this committee recommends to be built in the immediate future, that they may serve without important change to meet the future needs of navigation whenever channels having depths of 25 ft. or even 30 ft. are opened from the Atlantic Ocean to Lakes Michigan and Superior; for which depths there has been recently a strong popular demand, both in the United States and in Canada.

The proposed "Fairway," to be always open in the St. Clair River, shown in the present designs, has 27 feet clear depth at proposed minimum regulated stages during navigation season.

The proposed locks to be first built in the St. Clair River are designed of a clear depth of only 25 feet. The future locks for which location is provided and which are to be partly built in connection with the first installation, can be made 30 feet deep.

Obviously it would be a simple matter to change the designs of the fairway and of the first locks so as to give 30 feet clear depth, should the International Board conclude this on the whole more desirable than 25 feet.

Because of its appeal to the imagination of farmers and others, and its appeal to popular sentiment both in the United States and Canada, it is quite possible that this deeper waterway with 25 feet depth, (possibly 30 feet) may be soon provided for by Acts of the United States Congress and of the Canadian Parliament, notwithstanding the most careful estimates of structural cost, and of probable earnings, may show no money profit upon the investment for many years to come.

The present writer believes that a deep waterway from Duluth and Port Arthur to the Atlantic is sure to come within 25 or 50 years.

CO-OPERATION IN DISTRIBUTION OF COST

The Chicago Sanitary District heretofore has offered a large sum of money toward the cost of Compensating Works consisting of submerged weirs or other structures in the Niagara and St. Clair Rivers, sufficient to restore elevation to an extent equal to that caused by its diversion. Therefore, it may reasonably be expected to contribute a substantial amount **toward Regulation Works** that will accomplish all of this and do much more for its own commerce as well as for that of its neighbors, than if the work is **limited to only compensation for diversions.**

INTERNATIONAL CONTROL

Although the Canadian tonnage carried on the Great Lakes is smaller than that carried in United States ships, **the prospective hydro-electric developments on Canadian territory supplied with water from the Great Lakes, are much larger than those in prospect or possible on the United States side of the International Boundary.**

The Canadian Government has for a hundred years shown liberality in its constructions of canals and works for improving navigation on the Great Lakes and in its heroic work on the new Welland Canal now in progress, and the interchange of use of navigation channels between lakes without tolls or restrictions has long been of such a friendly nature, that it is unthinkable that means cannot be found for most friendly co-operation between Canada and the United States in building these additional great works for regulating elevation and discharge of lakes which will be of great benefit to both parties; or that means cannot be found for justly and satisfactorily apportioning to each country its fair share of the cost.

It is worthy of note in showing the friendly co-operation of past years that a large part of the expenditure by the United States Government for the new Livingstone Channel was on the Canadian side of the international boundary line.

Good precedents for satisfactory and amicable joint control of the proposed works for regulating the levels and discharge of the Great Lakes can be found in the co-operation of the two governments in many years past on various international waterways studies, and in the method by which the present regulating works at Lake Superior have been operated under the joint supervision of a United States engineer, Mr. Sabin, and a Canadian engineer, Mr. Stewart; also in the open and friendly joint supervision of the diversions for power at Niagara by Canadian and United States referees.

CONDITIONS FOR NAVIGATION

Before proceeding further with the description of the works for regulation of lake level and discharge which it is proposed to build forthwith, it will aid in a better understanding of the reasons for the designs presented in this report if the conditions which are to be satisfied in the operation of these works are again briefly described.

Navigation upon the Great Lakes in its present magnitude, both as to dimensions of vessels and as to quantities of freight carried, is of relatively recent growth, and perhaps has now attained nearly its maximum of tonnage development.

The original channels connecting the Great Lakes contained many shallows, also most of the lake harbors in their natural condition were of such limited depths that until less than half a century ago there was little opportunity for use of boats drawing more than about eight feet, and it is recorded that boats drawing more than about five feet could not pass between Lake Huron and Lake Erie until the connecting channels were artificially deepened.

The first large work of improvement was the building of the Weitzel Lock at Sault Ste. Marie in 1870 to 1881—60 feet wide at the gates with a depth of thirteen feet over its sills (See Warren Report, page 106). This was followed in 1887 to 1896 by the Canadian Lock and the Poe Lock with 18 feet to 20 feet over their sills. The present third and fourth locks have been completed since 1914 with 24½ feet depth over their sills at the stages existing at the time of the Warren Report, about 1920.* The U. S. Government has expended about $24,000,000 at the Sault St. Marie upon the locks and in dredging, and the Canadian Government has expended about $5,000,000. The annual cost of operation of the U. S. work is about $125,000 per annum.

These figures are of interest for comparison with the prospective costs of the work now recommended, but it is of interest to remember that the unit costs in dollars per cubic yard, at the time of the construction of the older works, were only about half those now prevailing.

In the meantime, the channels connecting Lakes Huron and Michigan were deepened and improved step by step, by dredging; particularly in the shallow delta channels at the head of Lake St. Clair and across the clay bottom of this shallow lake; by deepening the shoals at the Limekiln crossing, and by the construction of the broad Amherstberg Channel at the lower end of the Detroit River, 20.2 ft. deep; and the Livingston Channel 21.2 feet deep below lowest water in the Detroit River.

*Earth-tilt probably will lower the depths over all of the lower sills, at the rate of about 1 foot per century (see page 154).

The improvement of the St. Clair River was begun in a very small way between 1855 and 1858 by deepening one of the passes in the St. Clair delta.

Most of the deepening of channels by dredging appears to have been done between the years 1885 and 1897. The St. Clair Flats Canal was deepened to 20 ft. and made 300 feet wide, this work being completed in 1895. The dredging of the Grosse Pointe channel, 800 ft. wide by 20 ft. deep, and the removal of the shoals between Detroit and Lake Erie with a channel 600 ft. wide by 20 ft. deep was authorized and executed. In 1897, a channel 800 ft. wide by 20 ft. deep was cut through the bar at the mouth of the Detroit River.

In the Upper St. Clair River, the bed is of gravel, sand and hard clay. The removal by the original dredging of the skin or shingling of gravel that had been accumulating for countless ages on the river-bed near the head of the river, or where dropped by ice, would leave the uncovered surface much more easily scoured than prior to this dredging. In the lower St. Clair River this dredging is in clay or mud subject to natural erosion and to scour by the swift currents caused by the propellers of the big deep ore boats which work close to the bottom of shallow channels.

At the outlet of Lake Huron the dredging appears to have consisted mostly in cutting deep channels through the sand bars and gravel bars from 1 to 2 miles upstream from the narrow and deep natural channel at the head of the St. Clair River.

Also, various harbors around the lakes have been deepened by dredging and protected by breakwaters, so that now a vast commerce is carried on the lakes and great ships pass through the St. Clair River from June to November inclusive, with the interval between ships, counting those in both directions, averaging only about 15 minutes day and night for the entire 240 days of open season, and ships often come in greater numbers at shorter intervals for several hours in succession.

There were in commission in 1918 about 530 vessels of large size, averaging 20 round trips each per season of 30 weeks, from late April to early December, which gives an average of about 100 boats passing per day and a round trip for each boat in about 11 or 12 days. The season is nominally 240 days long, or about 34 weeks, but there are fewer boats running near the beginning and end of the season and there is a concentration in mid season.

There is hardly a river or harbor entrance in the world where a greater tonnage of shipping in motion is continually in sight than in the St. Clair and Detroit Rivers. Appendix F, of the Warren Report, pages 386-396, presents statistics of great interest regarding the traffic. On page 392 is a table from which it appears that the Detroit River is the most used waterway in the world, while the ship canals at the Sault are a close second. Duluth leads all the ports of the world in annual tonnage, notwithstanding its harbor is closed by ice during a third of the year.

The greatest factor in stimulating the building of larger ships and in causing the deepening of channels between the lakes was the discovery of vast deposits of iron ore in the Lake Superior region, and the gradual development of great mines in northern Minnesota in connection with steel works at Pittsburgh, Chicago, Cleveland and Buffalo. The transportation of coal from Pennsylvania westward as a partial return cargo for the oreboats also has had large development. Following the rapid agriculture development of the northwestern United States and of the vast grain producing areas of Alberta and Saskatchewan, the shipment of wheat also has had an important share in this commerce; but iron ore furnishes by far the chief volume of freight and the most urgent call for low freight rates.

The present conditions of transportation and the relative proportions of different kind of freight are shown in the following tables.

Notwithstanding the vast development of Chicago, Duluth, Cleveland, and Buffalo, as centres of distribution for manufactured products of almost every kind, the transportation of general commodities by the Lake boats, although considerable, has not attained any large proportion in competition with railroads and their superior facilities for collection and distribution of miscellaneous freight; as compared with shipments of ore , coal, grain and limestone for furnaces, etc.

TABLE OF BULK FREIGHT CARRIED

AVERAGE OF 4 YEARS ENDING IN 1918

(From Page 389 Warren Report)

		Per cent of Total
Iron ore East to Lake Michigan	10,000,000 short tons	
Iron ore East to Lake Erie	45,000,000 short tons	
Total ore	55,000,000 short tons	56.7
Grain East from Lake Michigan	2,000,000 short tons	
Grain East from Lake Superior	4,000,000 short tons	
Total Grain	6,000,000 short tons	6.2
Stone West to Lake Michigan	1,500,000 short tons	
Stone East to Lake Erie	4,500,000 short tons	
Total Stone	6,000,000 short tons	6.2
Coal West to Lake Michigan	13,000,000 short tons	
Coal West to Lake Superior	17,000,000 short tons	
	30,000,000 short tons	30.9
Grand Total, Ore, Coal and Stone	97,000,000 short tons	100.0

The following table shows the size of boats which must be provided for in the designs of regulating works.

DIMENSIONS OF 3 LARGEST FREIGHT VESSELS ON THE GREAT LAKES

Name of Boat	W.G. Worden	Col. J. M. Schoonmaker	Wm. P. Snider, Jr.
Length over all feet	625	617	617
Beam feet	50	64	64
Depth feet	32	33	33
Registered tonnage	8,074	8,603	8,603
Greatest cargo ever carried, short tons	13,721	15,148	15,292
Short tons load per tenth of foot draft	107.3	113.2	113.2

The largest passenger steamer is 100 feet wide but of much less length than the ordinary boats designed for bulk freight. It cannot pass the Sault St. Marie.

CLASSIFICATION OF LAKE FREIGHTERS BY SIZE

Typical Dimensions Length Overall	Beam	Number of Vessels in this Class	Cargo Capacity Short tons at 10 ft. draft	Increase of Capacity per 0.10 ft. of draft	Percentage of total yearly freight carried	Registered Tonnage
280	40	85	3,000	31	10	2,400
370	45	124	3,500	47	10	3,500
460	52	158	7,500	68	34	5,100
570	56	121	10,500	92	26	6,800
600	60	42	12,000	104	20	7,700

A suggestion that perhaps this Great Lakes shipping already has reached nearly its maximum of tonnage, is based on the probability that no very large increase over the present shipment of wheat and food products will come in future, and upon the obvious limitations in the Lake Superior ore supplies. The date when the best quality of ore will largely be exhausted has already been estimated. Lumber carriage already has largely decreased with the cutting off of the great pine forests of Michigan, Wisconsin and Minnesota and those on the Canadian shores.

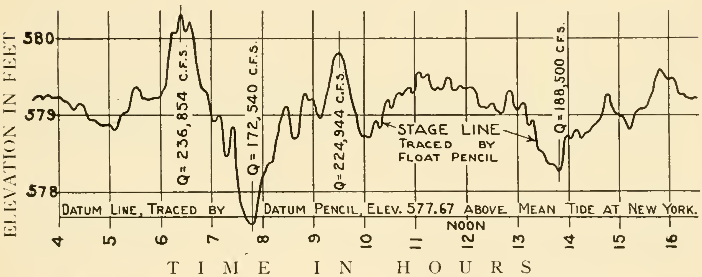
OSCILLATIONS OF LAKE LEVEL AND CLEARANCE REQUIRED

The importance of considerable clearance between bottom of boat and bed of the shallow channels connecting the lakes, is illustrated by the following example of sudden fluctuation in Lake Level on May 17, 1899, while current meter gaugings were in progress. In this case a change of 2.2 ft. in depth occurred within 1¾ hours.

This particular gauge was about ⅔ mile downstream from the Fort Gratiot Light, in position shown in map on page 399.

REPRODUCTION OF RECORD OF U. S. L. S. GAGE NO. 5 FOR MAY 17, 1899

At Head of St. Clair River



Quantities are computed by formula from corresponding gage heights.

Gage No. 5, normally at Mean Stage reads 578.304 when Sand Beach (Harbor Beach) Gage reads 580.479. Difference is 2.175 feet.

The greater sudden changes in levels at opposite ends of Lake Erie, mounting to 5 feet or more, caused by strong winds, described on page 201 are of interest in this connection.

Other interesting illustrations of large fluctuations in lake levels, caused by quickly passing changes in the barometer, or "barometric waves," are described by Mr. Frank Jermin, meteorologist, on pages 20–33 of the report of the Great Lakes Protective Association for 1923.

On August 19, 1921, while local thunder storms prevailed on Lake Michigan, the barometer showed sharp and irregular fluctuations on Lakes Huron and Michigan, with a barometric wave crossing from Milwaukee at the rate of 39 miles per hour.

From 7:20 to 7:45 p. m. the water at Milwaukee rose 1.5 feet, and then fell 1.0 feet by 8 p. m.: a change of **2.5 feet within about half an hour.**

Shortly after midnight following, or at about 1 a. m. on August 20, 1921, a **fall of 2.0 feet occurred within 10 minutes.**

On August 19, press reports told of startling phenomena at Grand Traverse Bay, beginning at 9 a. m. The water receded several hundred feet from the shore, and rushed back, at regular intervals.

Another example was given on Lake Huron, on September 6, 1922, at 10 a. m., following thunderstorms in early morning. The water at Presque Isle Point was 8 inches below normal, and at Thunder Bay Point, 2 inches above,—a difference of 10 inches in 28 miles.

At Alpena, Mich. on Dec. 31, while a storm of considerable energy was crossing, the water **rose and fell through an extreme range of 1.25 feet**, with minor pulsations, or having a period of about two hours between their crests.

Obviously such extreme differences of level must set up strong currents. At low stages of lakes, these wide and sudden fluctuations are a serious cause of marine accidents.

Also, these currents tend to cause a strong up-welling of the cold water from the great depths when they meet obstruction by shoals or by an opposing current, and thus produce irregular areas of low surface temperature and lessened evaporation.

A Great Seiche

The most notable instance in recent years, of large and rapid fluctuations in lake level, occurred on May 22, 1925, along the shore of Lake Huron from Alpena to Cheboygan. Possibly this was caused by the meeting and impact and momentum of two opposing currents, each set in motion by sudden strong barometric waves.

At about 5.30 p. m. the water at Rockport **rose five feet in six minutes and then fell, as rapidly as it rose, to eight feet below the highest point reached.**

This change in the lake level was followed by oscillations of gradually diminishing amplitude and apparently irregular time periods.

At Calcite, the water rose four feet above and fell five feet four inches below normal level, making **a range of nine feet four inches.**

About an hour before this phenomenon started, a thunderstorm passed apparently from west to east and the center of its path was north of Rockport. This storm moved rapidly, and **was attended and followed by sharp changes in barometric pressure.** Otherwise, the storm was not unusual.

Warnings About Lake Currents

It is of interest to know that for 11 years past Mr. Jermin, the U. S. Weather Bureau meterologist at Alpena, Michigan, has been sending out advisory messages regarding currents and fluctuations, lake levels, sea conditions and probable movements of ice; for the benefit of shipping on Lake Huron.

He states that in forecasting these conditions he has largely abandoned the wind theory as a basis, and **relies mainly on barometric waves as indicated on the weather chart,** as a basis for his predictions about currents.

He considers that the attempts of ship masters to estimate the amount by which they are being thrown off their courses **by wind, without proper attention to the drift caused by currents induced by barometric waves,** particularly in foggy weather, has caused many shipwrecks on the Lakes.

Low water greatly increases the number of accidents, from a grounding of heavily laden bodies and injuries from rubbing the bottom of the boat on shoals. This is discussed in the report of the Great Lakes Protective Association for 1922, page 17, which also mentions how these dangers are enhanced by fluctuations that unexpectedly occur.

Draft readers and dispatchers have been maintained to give warning of these sudden fluctuations at several danger points, and an illuminated bulletin board is maintained at night in the Amherstburg channel.

INJURY TO TRANSPORTATION BY LOW LAKE LEVELS

The great ore carrying boats are loaded to the maximum depth of draft that locks and channels will permit. It has been stated that each extra inch of draft on each of about 162 of the larger boats, increases the paying cargo of one boat in one voyage by about 75 tons to 100 tons.

The economics of mass transportation have doubtless been more highly developed by the lake carriers than by any other shipping in the world. The preceding tables show that many of the boats are upward of 600 ft. in length by 60 ft. beam and designed to draw 20 ft. to 24 ft. depth of water when loaded, and that 46 per cent of all the bulk freight is carried in boats upwards of 10,000 tons capacity of paying freight. These great boats are special tools, designed for extremely rapid loading and unloading, for a quick return voyage, and they present maximum economy of construction and operation in every particular.

For the purpose of obtaining proper rigidity in connection with their great length, many of the newer hulls built nominally for 20 ft. depth of draft to fit maximum dimensions of locks and channels, are, it is stated, for reasons of structural rigidity given sufficient depth of hull so that they could just as well be loaded to a depth of 22 ft.; perhaps to 23 ft. or even 24 ft., if there were sufficient depth of channel to permit this.

Nevertheless, during the low water of the past year, the largest boats passing through Lake Superior, Lake Huron and into Lake Erie, have found it possible to load only to a depth of about 18 ft.

Much testimony has been given regarding the disastrous effect of the recent lowering of lake levels upon the economies of the shipping industry, and to the effect that each inch of depth lost in loading because of shallow water represents a loss of $1,000.00 per year in net earnings on freight for each of the larger boats of 10,000 to 15,000 tons cargo capacity. A close watch of lake elevations is kept by the ship masters and when cargo space is in demand, each boat commonly is loaded to the limit that can get over the lock sills or through the channels in harbors and between the lakes, but commonly with a large margin for contingencies and sudden change of level from seiche or storm.

Although in dealing with averages we may estimate values and damages on the basis of single inches of depth of draft, one should not lose sight of the fact that **either one of the Great Lakes may within an hour or two, and without warning, have its water surface at the shallow channels near either end, suddenly drop more than a foot; because of the silent passing of a barometric wave.** Also strong winds, continued several hours, may cause far greater change in depth. (See pages 201–203.)

RECOMMENDED DRAFT FOR LAKE FREIGHTERS IN THE YEAR 1918

The following table, from page 387 of the Warren Report, is presented to illustrate the relation of practical depth of draft to lake levels, its variation from month to month through the navigation season, and the care with which these matters are looked after by the Lake Carriers Association, which publishes these notices in the interest of avoiding damage to vessels by grounding, and as affecting marine insurance.

These recommendations as they stand in the table below, do not in all cases appear consistent. The differing risk in different times of the year of sudden changes of depth caused by strong winds or seiches, may affect this. The gales which suddenly depress one end of Lake Erie 5 feet commonly come in April or after October.

For example, 1.0 ft. more draft in Lake Superior is recommended on June 6 than on April 24 although elevation of water is only 0.2 ft. greater, and in certain other comparisons the depth of loading recommended is not in direct proportion to the elevation of the lakes.

Date Recommended	Draft	Elevation of Water level
1917		
April	20 ft. 0 inches for Lakes St. Clair and Erie	572.6
June	20 ft. 4 inches for Lake Michigan	
"	20 ft. 2 inches for Lakes St. Clair and Erie	573.6
Aug. 23	20 ft. 10 inches for Lakes St. Clair and Erie	573.6
Sept. 5 to end of season	21 ft. 10 inches for Lakes St. Clair and Erie	573. to 572.6
1918		
April 9	21 ft. 0 inches for Lake Michigan	581.4
April 24	19 ft. 6 inches for Lake Superior	601.5
June 6	20 ft. 6 inches for Lake Superior	601.7
" 6	20 ft. 6 inches for Lake Michigan	581.6
" 6	20 ft. 6 inches for Lakes St. Clair and Erie	572.6
Oct. 17	20 ft. 0 inches for Lake Superior	602.5
" 17	20 ft. 0 inches for Lake Michigan	581.2
" 17	20 ft. 0 inches for Lakes St. Clair and Erie	572.3

In 1924, the elevations of Lakes Michigan, Huron, Erie and Ontario averaged a little more than a foot lower than in 1918, for which year the above recommendations were made. Lake Superior was held up by its regulating gates. It has been stated that only 18 feet depth of draft was safe in the latter part of 1924.

Ordinarily, depth of draft is limited by depths in the channel dredged through the bed of Lake St. Clair.

Many estimates have been made of the money value of each foot, and of each inch, of increased draft available for the big boats carrying ore and grain from Lake Superior ports to Lake Erie ports; and it is doubtless true that each inch lost in carrying capacity by one of the larger boats, of which several hundreds are in use, means a loss of earnings during each navigation season of about $1,000 to that particular boat, providing, of course, business conditions are such that cargoes are freely offered. It has been estimated by several men exceptionally familiar with the actual conditions, that one inch lost in depth of draft causes an annual loss of $500,000 in freights which must be refused when water is as low as during the past few years. Estimates presented in detail on page 390 of the Warren Report confirm the accuracy of these statements, providing there is a demand for all available cargo space. These state that 0.10 foot loss of depth may cause a loss of $590,000, in a single year, in the 25 round trips of the 530 large vessels, equivalent to **nearly six million dollars per year for one foot loss or gain in navigable depth.**

Some doubt attaches to the broad or precise application of estimates of this kind, because of the fact that in recent years there have been frequently more boats than cargoes available. Nevertheless, it seems certain beyond all doubt that there have been losses measured by millions of dollars per year caused by the low lake levels of recent years, although it may be difficult to fix the precise amount.

The Chief of Engineers in his annual report for 1906, page 849, shows the value of a foot of draft on the Great Lakes to be $100,000,000.*

On page 392 of the Warren Report, Mr. Richmond estimates that the increased cost of transportation throughout the Great Lakes and St. Lawrence system due to the actual lowering of surface, now aggregating about one-half foot on Lakes Michigan and Huron and three-fourths of a foot on Lake Erie, caused by the lowering of lake and river levels by the several diversions through Chicago, Welland, Erie and Power Canals results in an economic loss of $4,713,000 per year.

The estimate of $500,000, loss per inch in depth, given above was for the shorter average distance on routes to and from ports between Duluth and Buffalo but multiplied by 5½ inches depth lost, makes up a total of $2,750,000 per year.

Since climatic causes produce differences of about four feet in lake elevations, between the extremes of dry-year cycles and wet-year

*Another view point on the savings from water transportation on the Great Lakes is that if it had not been available, no such vast tonnage of iron ore from around Lake Superior could have been economically transported by rail to Pittsburgh and Buffalo, and the whole course of development of mining and steel making would have been changed, perhaps largely to foreign ores, and with steel at higher cost.

cycles, which is about six times as much as the sum total of all lowering in any lake caused by all of the diversions, it is plain there is a vast economic gain to be had, measured by many millions of dollars each year, if the extreme lowering from climatic causes can be largely prevented.

Doubtless it is true that a majority of the largest boats, which during the past year have been compelled to operate on a draft of 18 ft. could equally as well, and with hardly perceptible increase of cost, be loaded to a draft of 22 ft., or in many cases, of 24 ft., had sufficient channel depth been available, and it also is true that with the revival of business and the natural growth of the two countries, this additional capacity surely will be needed at an early date.

Another method which has been used in estimating damage caused by loss of depth, which should apply equally to gain by increase of depth, is by estimating the cost involved in deepening all the various lake harbors and connecting channels so as to accommodate six inches of increased draft, and thereby offset the effect of the Chicago diversion. It was estimated by the International Waterways Commission in 1907 that about **6 inches deepening would cost about $12,500,000. At the prices of today this figure would be about doubled.**

It is plain that to gain 2 feet increased depth by dredging would cost far more than four times the cost of this first six inches, because of the vastly larger area over which dredging must be done, and because of the added cost of deepening locks; and that the total cost of gaining two feet extra depth by dredging channels and harbors would be far greater than the cost of the proposed regulation works, by which the same result can be more quickly attained.

There is no need for new refinements in estimating the loss caused by decreased depth, and no need of new methods for computing the gain by increased depth, in order to show that complete regulation of the Great Lakes by means of dams, gates and sluiceways in the St. Mary's, St. Clair, Niagara and St. Lawrence Rivers, is one of the most practicable and profitable works of river and harbor improvement that can be undertaken anywhere within the limits of the United States and Canada.

Accepting the figure of $500,000 per year, per inch of lost depth as the actual increased cost of transportation between Duluth and Buffalo or intermediate ports, and assuming that this, like other good rules, works both ways and that it is applicable over a wider range, up to 24 inches, **the proportional gain from 24 inches of increased draft would be $12,000,000 per year.**

A much larger figure than $12,000,000 gain per year will be arrived at by proportion from Mr. Richmond's more complete estimate of $4,713,000 on the preceding page, for the increased cost of transportation due to lowering of lake and river levels amounting to an average of about 5½ inches in Michigan-Huron and 9 inches in Erie, caused by the several diversions of water all along from Sault St. Marie to the St. Lawrence inclusive. It appears reasonable to measure in both directions by the same yard-stick, but account must be taken of the actual demand for cargo space from year to year.

If the actual gain over a term of years should prove to be only one-half, or only one-fourth of the $12,000,000 per year, estimated above, the gain to navigation would be sufficient to pay generous interest and depreciation charges upon a sum larger than the estimated cost of the regulation works now proposed, both in the Niagara and St. Clair Rivers.

Beyond this **there would remain, as a bonus, the great gain to future water power coming from the larger regulated discharge in years of small rainfall, and days of small natural yield;** also there remains another and more immediate bonus, in the great improvement in the scenic beauty of Niagara, and in the much needed extension to Buffalo Harbor provided for in the designs now presented.

Recalling the estimate of the Chief of Engineers Report of 1906, page 849, that each foot of draft on the Great Lakes has a value of $100,000,000, it appears that the prospect of obtaining an increase of 2½ feet in addition to 10,000 or 20,000 c.f.s. larger minimum flow, the preservation of Niagara, and the increase of terminal harbor to 20 miles downstream from Buffalo, all for an expenditure of only about $35,000,000, should be extremely attractive.

ANALYSIS OF DATA PRECEDENT TO NEW DESIGNS

The preceding facts and figures have been presented in order to more fully justify the action of this committee in proceeding on broader lines, than the discussion of compensation works sufficient only for remedying the Chicago diversion.

In the pages that follow, many more facts and figures will be given, which were made in course of the preparation of the designs now presented, in order to be certain of the practicability of the works proposed, under all circumstances, and which data may be useful in future discussions.

The problems presented here are on such a large scale and of such far reaching importance that while proceeding with designs for regulation works, all available records as to lake elevations and discharge, the certainty and precision with which each was determined, and the causes of their fluctuations, were analyzed. A brief résumé of this anaylsis is given in Appendix No. 1. Data on height of water surface, and data on rate of discharge must be considered separately, although the long term estimates of discharge depend on the records of elevation.

In early years, or prior to the Deep Waterways Report of 1900, much more attention was given to measuring elevation than to measuring the discharge. The elevations of surface for all of the lakes, being of great importance to navigation and to citizens and municipalities possessing structures located along their shores, have been measured and recorded day by day throughout the past 65 years, with remarkable thoroughness and accuracy; particularly during the past 25 years. In the records of more than 30 years ago, it is said there are some minor uncertainties about frequent verification of the stability of some of the gages, but no probability of errors large enough to affect the solution of the present problems. There are fairly reliable records of lake elevations that go back about 100 years and show climatic variations and cycles of high water and low water somewhat like those of recent dates. The elevations of the several gage datums above mean sea level have been re-determined by lines of precise levels run by the U. S. Coast and Geodetic Survey in 1903, with the utmost precision practicable and in recent years are frequently verified.

The growing importance of waterpower development now makes accuracy in measuring and recording the daily discharge highly important; and now that control of discharge by storage of surplus water in seasons of large rainfall and its release in seasons of scarcity is under investigation, it becomes more important than heretofore to know with what degree of accuracy the mean monthly discharges reported in the records of the U.S. Lake Survey, etc., have been measured, or estimated.

The accurate measurement of the discharge of the Great Lakes seems never to have been seriously attempted until 1869, and after two seasons of work largely experimental in nature, no other direct gaugings were attempted for about 30 years.

A very elaborate and precise series of gaugings of discharge was carried on during the summer months from 1889 to 1903, at the various lake outlets. Within the past 20 years few additional direct gaugings have been made. By means of these careful direct gagings made during only relatively few months out of the past 65 years, in connection with careful observations of the elevation of the lake during each particular gaging, diagrams like that presented on page 30 have been prepared which show the rate of discharge corresponding to any height in the lake.

A formula corresponding to the mean line of each such diagram also has been prepared from these extensive series of gagings with current meters made at the several lake outlets in 1896–7–8–9, 1900–1–2, and the check series of 1907–8–9–10 and 1913. The discharge is estimated for all ordinary purposes by means of these formulas, or rating diagrams for each lake, which show the quantity discharged corresponding to any given elevation of the lake. The discharge for any day or month is determined from these rating diagrams or formulas by means of the records of elevation, at all times when the lake outlets are not obstructed by ice, with a degree of accuracy sufficient for all practical purposes.

The accuracy of the record of daily or monthly discharges for the past 65 years or more, depends upon the degree of certainty with which these rating curves can be applied to the record of lake elevations, and this depends on permanence of channel bed and on freedom from ice.

Taken as a whole, this series of current meter gagings at all of the Great Lakes outlets, made at various times between 1896 and 1913, comprises the most elaborate, precise and accurate discharge measurements on rivers of great size that have been made anywhere in the world, and their precision is all the more remarkable because of the difficulties of the situations; particularly those connected with the great width and great depth of the cross sections at which the gaugings were made and the frequent changes in elevation of lake surface, with corresponding changes in velocity, during the several hours required for making one complete measurement across the section.

The chief possibility for lack of precision of measurement is found in connecting up the accurate gagings of quantity with the somewhat variable simultaneous lake levels, so that having given a record of elevation on a given day one can pick off from the diagram, the rate of discharge. At Lake Huron the difficulties of establishing precise relations between elevation of lake and rate of discharge seem to have been more serious than at other lake outlets.

In the earlier years of the record, actual accurate gagings of the discharge of Lake Huron were few and far between, and there may be some question of the precise application of formulas of discharge derived from the current gagings of recent years to the old records of lake elevation because of the possibility that the area, or shape controlling the outflow from Lake Huron has been materially changed by dredging and scour from the condition which existed at the time of gaging.

If the lowering of Lake Huron caused by dredging and scour has not been more than 0.25 ft., which now seems more probable, after the studies of earth-tilt, then the over-estimate thus caused, for these early years, will be only 3 per cent.

The few current meter gagings of the St. Clair River made 50 years ago agree well with those made 20 years ago.

In winter, during the period when lake outlets are obstructed by ice, an important margin of error and uncertainty in the measurement of the discharge exists in the estimates for Lake Huron, and to a much smaller degree in those for Lake Erie. This detracts from the accuracy of the mean yearly values given for discharge in the tables prepared by the U. S. Lake Survey, particularly in early years. For recent years greater care has been taken to estimate the lessening of discharge caused by ice, but there are times when ice covers much of the river surface, and particularly while ice gorges exist, in which the record of quantity of water discharged by the St. Clair and Niagara Rivers is still subject to a considerable uncertainty.

Nevertheless, the figures which recently have been supplied by the U. S. Lake Survey office, and used in the computations affecting the design of these proposed regulation works, certainly are precise enough for most present practical purposes.

During the controversy about the Chicago diversion, reported in the Transcript of Testimony before the U. S. Supreme Court, filed August 23, 1923, the precision of some of these gagings was seriously questioned by experts called by Chicago, and strongly re-affirmed by witnesses called by the government, all to the extent of more than a thousand printed pages of testimony. These questionings have been given serious study by members of this committee, and although the conclusion has been that **the accuracy surely is sufficient for present purposes,** the questions raised are of such interest that they will be discussed briefly in Appendix No. 1.

HIGH AND LOW CYCLES IN LAKE LEVELS

The records of 65 years' observations of daily height in each of the Great Lakes have been plotted in form of diagrams of monthly averages and published in the yearly reports of the U. S. Chief of Engineers and are presented in the folding diagram of mean monthly lake levels which follows on page 198A.

These mean monthly elevations show long and repeated cycles of rise and fall, over a range of from three to nearly five feet in height in the several lakes; all lakes moving up or down, generally in remarkably close agreement, and in cycles of from ten to twenty years in length. Incomplete records of lake heights going many years further back than 1860, show similar cycles of rise and fall.

The varying mean monthly rates of discharge for each lake corresponding to these elevations are given in a similar diagram on page 235.

In the 65 years since January 1, 1860, the folding diagram of lake elevations shows six irregular, long-term cycles of high and low levels in all of the Great Lakes.

The dates of the successive principal highs and lows, and the lengths, of cycles have been as follows:

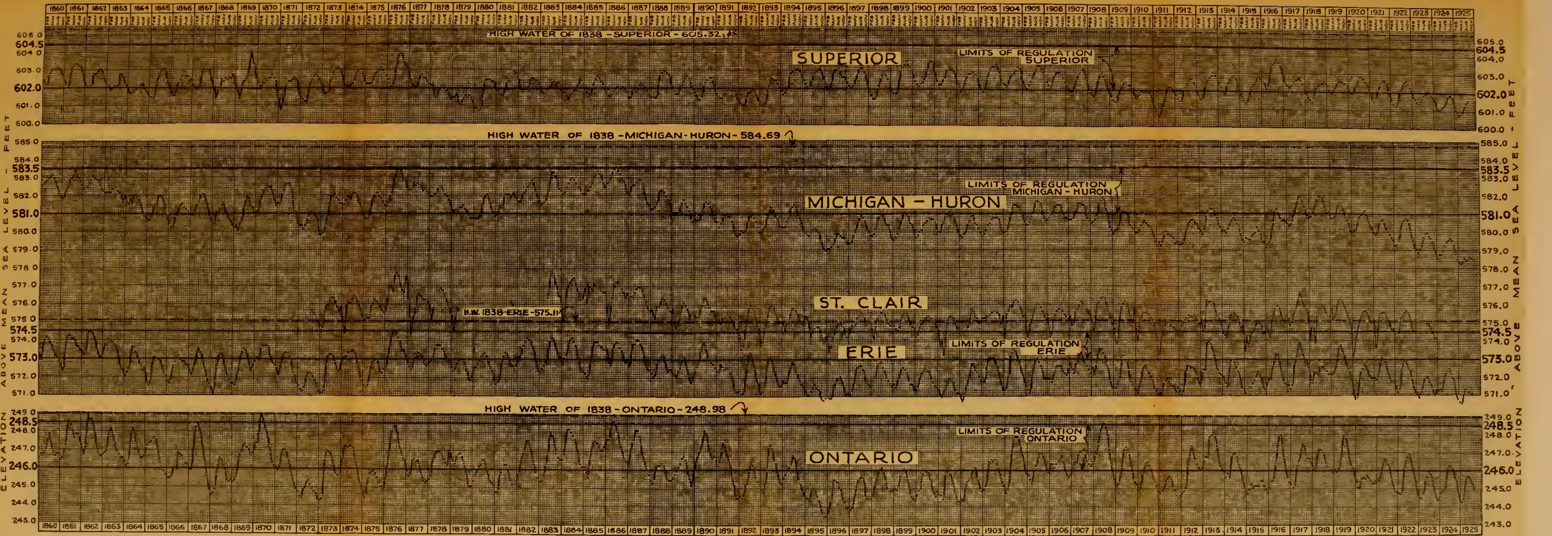
High	Low	Length of Cycle High to High	 High to Low
1861	1866	———	5 years
1870	1873	9 years	5 years
1876	1880	6 years	5 years
1886	1892	10 years	6 years
1894	1896*	8 years	2 years
1904	1911	10 years	7 years
1917	1924	13 years	7 years
Average length of cycle		9.3 years	5.3 years

*It is of special interest to note that in 1896, or 4 years prior to the opening of the Chicago Canal, Lakes Huron and Michigan and Erie were about as low as during the past year, 1924, and that Ontario was about 1 foot lower.

Upon this diagram of elevations of lakes heavy horizontal lines have been drawn which show the relation of the actual heights observed in the past to the maximum and minimum levels proposed for the future.

The heavy dotted lines show for comparison the record high-water level of 1838. Since Huron and Michigan form practically a single lake, because of their free connection through the broad deep straits of Mackinac, and stand always at substantially the same level in each monthly average, one line has been drawn for both lakes.

Lakes Huron, St. Clair and Erie are plotted to the same scale of heights, which shows true relation of their elevations.



MONTHLY MEANS OF ELEVATIONS OF WATER SURFACE OBSERVED DAILY UPON EACH OF THE GREAT LAKES - AND PROPOSED LIMITS FOR FUTURE REGULATION

CAUSES OF CHANGE IN ELEVATION AND DISCHARGE OF THE GREAT LAKES

As stated on a previous page, navigation and most other matters dependent upon lake levels, now suffer much disturbance from the continual changes in the elevation of the lakes, also from changes in their discharge.

It is of the highest importance to study the several causes of change in lake levels and their effects carefully before proceeding with designs of regulation works, and before attempting to draw the line between improvement of navigation and the improvement of water power, and before reaching a decision as to the extent to which the surplus waters of years of large rainfall or of small evaporation can be put in storage and carried over to be drawn on for power or navigation in time of need, and before deciding upon the limiting elevations between which control is to be maintained.

There are at least eight different causes at work producing the changes of elevation shown in the records of the last sixty-five years.

Changes Caused by Nature

1. The greatest single cause of change in lake elevations is long continued differences in total annual rainfall and evaporation. These show their effect in long-term cycles with periods of seven years, or longer, of rise or fall. We have records of rainfall at a hundred or more stations within the Great Lakes region, from which the wide-spread differences in annual and seasonal rainfall can be determined. These records show that the total rainfall over wide areas is more than 50 per cent greater* in some years than in others and that variations from 10 per cent above the long term average, to 10 per cent below this average are common.

   Evaporation has an uncommonly large effect in the elevations and discharges of the Great Lakes, because of the relatively large proportion of water surface in the catchment area, and important changes in the depth of evaporation from year to year, which we have no present means of measuring, may be produced by differences in temperature humidity and total wind movement.

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*At Chicago, in the climatic year from July 1, 1881 to June 30, 1882, rainfall was .... 49.89 inches
At Chicago in 1894–5 rainfall was only .... 22.87 inches
At Detroit in 1881–2 rainfall was .... 48.09 inches
At Detroit in 1894–5 rainfall was .... 19.91 inches
At Duluth in 1881–2 rainfall was .... 50.28 inches
At Duluth in 1894–5 rainfall was .... 21.56 inches
Thus, in the wet year the precipitation was about 2.4 times that in the dry years.

2. Each lake ordinarily stands about one foot higher late in the summer than near the end of winter. This rise is chiefly due to the greater rainfall in the spring, the larger spring stream flow into the lakes, to the release of ice-bound water in the spring months, and to the small evaporation loss during the late-spring and early-summer. It is of interest to note the small amount of lag in the course of the transmission of the high and low seasonal peaks, all along from Superior to Ontario.

Later in the year the drop is caused both by the lessening inflow from rain and by the greater evaporation of late-summer, and when winter begins and small tributaries become ice bound, the inflow becomes diminished further and the lakes fall to their lowest levels about the end of January.

3. Brief and sudden changes in height of one or two feet or more within 2 or 3 hours, caused by wind or changing barometer are common near the ends of each of the Great Lakes, excepting Lake St. Clair, which because of its smaller size is mostly immune. This is fortunate because lack of depth in the dredged channel through this shallow lake is commonly the feature which limits depth of draft in the large ore boats.

These oscillations are of different kinds and from different causes, and nothing can be done to control them. The effects of strong winds and barometric waves always have been and always will be among the important problems of navigation; most serious when lakes are lowest.

Tides

Lunar and solar tides are present in the Great Lakes,* and although so small as to be masked by the changes of level caused by barometric waves, they are noteworthy. Lieutenant J. D. Graham is said to have determined a lunar tide of one and three-quarter inches and a spring tide of three and one-half inches at Chicago. General C. B. Comstock reports a lunar tide of one inch at Milwaukee, and a spring tide of one and three-quarter inches at the west end of Lake Superior.

Seiches

Seiches or sudden brief changes in the local lake level caused by the passing of a barometric wave over the region, are next in order of magnitude. These oscillations frequently amount to not more than four or six inches, but sometimes have an

*Mentioned by Dr. Grove Karl Gilbert in U. S. Geological Survey Report for 1897, page 618, on "Earth Movement in The Great Lakes Region."

amplitude of two feet or more in Lakes Superior and Erie. That end of the lake where the barometer stands lowest rises, and the opposite end falls, as the wave passes. Their period from low to high, and back to low, may be from one hour to thirteen hours, and varies in the different lakes according to the direction of the barometric wave, whether lengthwise or crosswise of the lake. Moreover, a reflection of the water wave against the lake shore may become superimposed upon the original oscillation, apparently shortening its period.

In Lake Erie, the normal lengthwise period is found to be 13.0 hours at Buffalo. At the Straits of Mackinac the period for a complete oscillation is found to be about 7 hours.

Some examples of extreme seiches on Lake Huron are given on page 188.

Wind Effects

The greatest oscillations in lake level are those caused by strong winds blowing for a long time from one direction. Lake Erie appears particularly susceptible to these wind effects because of its relatively shallow depths, and because of its greatest length lying in the general direction of the strongest winds.

Extreme Changes in Level Caused by Gales on Lake Erie

An admirable review of the effect of great gales on the water level of Lake Erie, prepared by Engineer William T. Blunt, may be found in the first report of the U. S. Deep Waterways Commission, published in 1897, on pages 155 to 168. Mr. Blunt says, in brief: "Strong westerly and easterly winds are quite frequent, as nearly every storm crossing the country . . . passes near enough to Lake Erie to be felt. Even the West India hurricanes, which usually follow up the Atlantic Coast, extend their influence as far as this lake, and occasionally, as in October, 1893, veer across and pass directly over it.

Generally speaking, if the storm center (indicated by lowest barometer) pass to the northward of Lake Erie, the most severe wind will be from the westward; if it pass to the southward, severe easterly winds will result. By far the greater number of important disturbances pass to the northward, consequently westerly gales are more frequent. These usually occur in the fall of the year when vessels are endeavoring to close the season with a 'few more' trips, so that their importance is generally magnified over that of easterly gales, which more often occur in the early spring before navigation fully opens. The effect of westerly winds upon the water surface is generally greater than that of easterly winds. The storm center approaching from the westward causes the gale to begin earlier at Toledo than at Buffalo, consequently the westerly gale pushes the water ahead of it, while the easterly gale draws the water toward it." . . .

. . . "The most severe easterly gale commonly occurs in or near April, raising the water four to six feet at the west end of the lake and lowering it about the same at the east end. The most severely westerly gale ordinarily occurs in or near October, lowering the water 7 to 8 feet at the west end, and raising it 5 to 8 feet at the east end. Changes of 2 to 4 feet (or a total of 4 to 8 feet in the length of the lake) are of so frequent occurrence as to be considered common, and not heretofore matter of special record."*

Mr. Blunt presents tables showing the extent, duration and effect in raising the water, caused by 29 westerly gales and 29 easterly gales within the 9⅓ year period from October 1886 to December 1895. Thus there were about 6 disturbances of this kind per year, ordinarily of about 3 feet up at one end and about 3 feet down at the other end of the lake.

Mr. Blunt presents, with much fullness of detail, the effects all along the south shore of Lake Erie, of a severe gale on October 14, 1893, in course of which the lake level at the Amherstberg gage fell 5 feet, while at the Buffalo gage it rose 5.3 feet. During this one storm the range at both Erie and Buffalo was from a minimum of -0.8 ft. and -2.8 ft. to a maximum of plus 2.6 ft. at Erie and of plus 5.3 ft. at Buffalo, thus giving a range of 8.1 ft. in height of the lake at Buffalo during this one storm.

In many cases, with storms of a cyclonic character, the water is first driven by the wind in one direction and later, after the storm center passes, is driven in the opposite direction, thus increasing the return phase of the cycle.

Mr. Blunt remarks: "It is worthy of note that at Toledo, no matter from what level the fall starts, nor how severe the gale, the limit of fall seems to be 7 or 7½ ft. below mean level, and that within about 9 years it has been 7 feet below mean on seven occasions."

The most extreme levels reached at each end of the lake in westerly gales, occurred in the storm of January 10, 1889. At Buffalo the extreme actual level was 7.8 ft. above mean level, and the rise from the prevailing level was 8.2 ft. At Toledo, the extreme actual level was 7.5 ft. below mean level, and the fall was 7.1 ft. This storm was of Texas origin and passed well toward the west and north of the lake, the gale reaching an extreme velocity of 82 miles per hour, with a maximum of 55 miles per hour at Buffalo. This storm gave a difference of level of 15.3 ft. between the two ends of the lake, several other occasions show differences of 12 to 14 feet.

The lake level at Toledo fell 3 ft. in one hour on October 15, 1886, following a partial recovery on the second day of a heavy gale. At Buffalo, on November 25, 1895, the water under a northeast gale first fell to 3.4 ft. below mean level at 7 a. m. and under the southwest wind on the following day rose to 5.6 ft. above mean at 11 a. m., and then fell again to 3.1 ft. below at 1 p. m. This gave a fall of 8.7 ft. in 5 hours.

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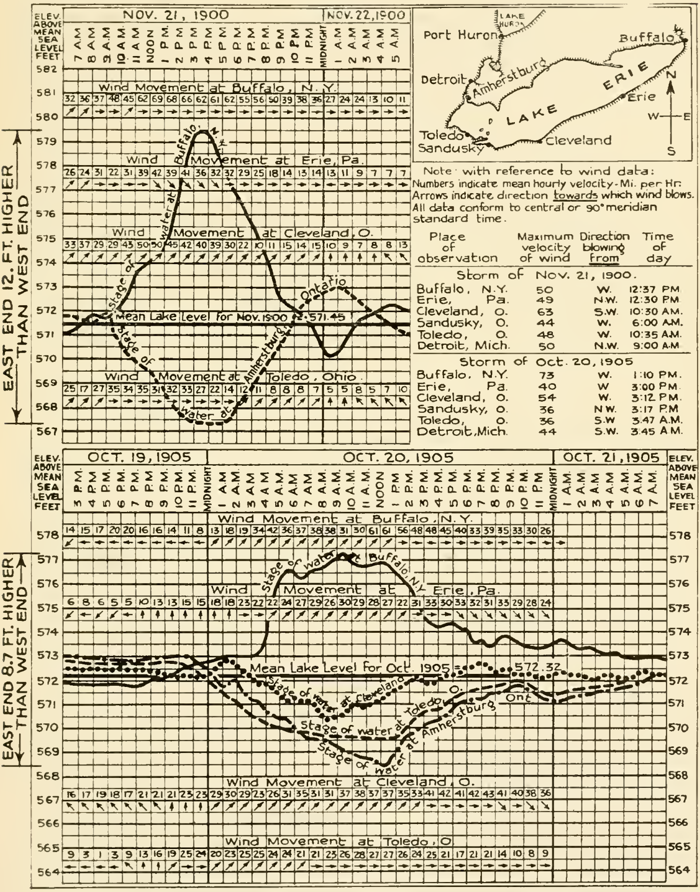
*On the general subject of lake levels Mr. Blunt makes reference to "an extremely valuable and exhaustive paper written in 1859 by Charles Whittlesley, and published in "Smithsonian Contributions to Knowledge," Vol. XII, entitled "Fluctuations of Level in North American Lakes," which gives the results of his researches as far back as 1788.

The following diagram shows more in detail the progress from hour to hour in two additional examples of extreme and rare fluctuations in height of Lake Erie caused by wind. It was given the writer by Dean Haskell.



EXAMPLES OF EFFECT OF STRONG WINDS
ON HEIGHT OF LAKE ERIE

THE HAYFORD STUDIES

A remarkably elaborate study of the effect of wind movements on the levels of the Great Lakes* has been in progress for fourteen years under the direction of Professor John F. Hayford, Head of the Civil Engineering Department of Northwestern University, and formerly Chief of the Department of Geodesy in the U. S. Coast Survey. This investigation has been supported by the Carnegie Institution of Washington as a part of a larger investigation, covering a much broader field.

The first volume descriptive of this research and its methods of analysis was published in October, 1922. The second volume giving the results from applications of these theories was well advanced toward completion at the time of Professor Hayford's death; and the writer is infoımed by the President of the Carnegie Institution that arrangements are now being made for carrying it to completion.

The chief object of this particular research was to find convenient means for determining the true average level of any of the lakes at any time, from the records of gage heights and wind movements, etc. which for many years past have been maintained at several points.

Professor Hayford had proposed that these refinements of measurement of true average lake level be used in obtaining:

(1) More precise information about evaporation from the Great Lakes.

(2) A more precise measurement of the rate of the tilting of the earth in the Great Lakes region.

(3) The general purposes of future precision in estimates for purposes of storage, release, and lake level regulation.

At present, due to the causes mentioned above, it is plain that a simple averaging of the observations made at any time by existing gages does not precisely give the level of the lake.

Professor Hayford expected that a continuation of these studies would lead to an accurate determining of the laws of evaporation from the extremely large water surfaces. To attain this end it was proposed

*"Effects of Winds and of Barometric Pressures on the Great Lakes," by John F. Hayford, research associate, Carnegie Institution of Washington, October, 1922; 7 x 10 inches, 133 pages and 13 plates.

to consider each of the Great Lakes in turn as an evaporation pan, and to evaluate from day to day: (1) change in water content; (2) water income; (3) water outgo, including evaporation.

To accomplish this purpose it is necessary to evaluate the change in content from day to day with great accuracy. The change of content is measured by the change in elevation from day to day of the mean surface of the whole lake. Each recording gage measures the change in elevation of the surface of the lake at the point at which the gage is located. Formerly the only feasible way to fix the elevation of the mean surface of the lake was to take it as equal to the mean of elevations at the two or three points on the lake at which first-class gages were operating.

Soon, as an outcome of this long and tedious investigation by Professor Hayford, the elevation of the mean surface of the whole lake may be determined on any day by applying the known corrections for wind effects and barometric effects at any gage, to the observed elevation for that gage. The proper weighted mean for the several gages may be taken and the few abnormal values may be detected and rejected by a definite criterion.

It appears that from observations at Mackinaw alone the mean elevation of the whole of Lake Michigan-Huron on any day may possibly be determined with a probable error less than plus or minus 0.010 foot. From the three stations, Milwaukee, Harbor Beach and Mackinaw together, this probable error may be reduced still more. It appears that the change in elevation of the mean surface of the whole of Lake Michigan-Huron in one day may possibly be determined with a probable error less than plus or minus 0.007 foot — an accuracy hitherto unattainable.

Professor Hayford says further:

"The vision is gradually taking form that the elevation of the water surface of each of the Great Lakes must be regulated by movable dams, or the equivalent, for the benefit of navigation, for the benefit to be derived in connection with the development of power in hydroelectric stations on the connecting streams, and to provide for the increased use of the water from Lake Michigan-Huron for sanitary purposes at Chicago. It is now clear that the return to the people of the United States from such regulation would be many times its cost.

"When that regulation becomes a reality, as it certainly will in due time, it will then become important to detect each fluctuation in elevation of each lake surface as soon as possible after it occurs and as accurately as possible. Each fluctuation must be detected soon after it occurs in order that the desirable change in regulation may be made. It must be detected accurately, because the total range within which the regulation must operate is small, and the means of regulation, the movable dams or the equivalent, will produce but very slow alterations in lake elevations. The quantities to be dealt with, for the desired valuable regulation, are hundredths of feet of elevation rather than tenths. The promptness and accuracy with which all fluctuations may be recognized is greatly increased by the outcome of this investigation. This is indicated in part by the comments on accuracy made in connection with the proposed application to the study of evaporation. It may be emphasized from another point of view by noting that there are frequent periods of 10 days or more on which the observed elevations at a gage are continuously too high or continuously too low to represent the elevation of the mean lake surface."

The results of this investigation, in the form of corrections for wind effects and barometric effects, and detection of abnormal values by certain criteria, should be applied to regulation of the Great Lakes,

(a) Directly, to furnish a more accurate knowledge than would otherwise be possible, day by day, of the actual mean elevation of the whole surface of each lake, and therefore of the total water content of the lake, and

(b) Indirectly, by enabling the laws of evaporation* and of run-off into the lake to be determined and understood in such wise that a forecast of the total yield of water to each lake for weeks and possibly months in advance may be made with much greater accuracy than would otherwise be possible.

*These important matters of Earth-tilt and Evaporation have been discussed at length in preceding pages.

Changes in Level caused by Ice

4. Temporary holding back of inflow, varying in amount from one year to another, may be produced by deep freezing of tributary streams.

In extremely cold winters, an important increase in the level of a lake may be caused by clogging of the out-flowing stream by ice. An ice jam in the St. Clair, Detroit or Niagara River, or an obstruction of discharge by an uncommon extent of ice-cover, will cause the lake upstream from the obstruction to rise, and cause the down stream lake to fall.

In some winters the discharge of the St. Clair and Detroit Rivers has been reduced about one-half for a period of about a month by ice obstructions, in other winters there is very little obstruction of discharge by ice.

The clogging of the St. Clair River, shown in diagram on page 36, in the severe winter of 1901, is shown by computation to have raised Lakes Huron and Michigan by 0.53 ft*.

The discharge of the Niagara River is seldom reduced by ice by more than about 5 per cent for a month, although for brief periods the reduction by ice may be 10 per cent.

The holding back of discharge by the increased friction of an ice covering in the St. Clair River, and by an occasional ice jam, keeps Lakes Michigan and Huron continuously averaging about half a foot higher than they would stand were the St. Clair River always free of ice. **The downward readjustment of level following such disturbance is much slower than the rise,** and the cumulative effects of obstruction for several years overlap.

Changes of Level Caused Artificially

5. A permanent lowering of uncertain amount, which, until recent studies of earth-tilt was thought, by several able investigators, to be somewhere between six and twelve inches in the elevation of Lakes Michigan and Huron as compared with Lake Erie, occurred about 30 or 35 years ago. After allowing for probable effect of earth-tilt it now appears probable that this permanent lowering does not exceed 4 or 5 inches.

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*The gage heights before and after the ice obstruction show that without this obstruction the discharge would have been 193,000 c.f.s.

The actual discharge shown by the diagram from Jan. 15 to April 30 has a weighted average of 119,000 c.f.s. for 105 days. Thus the retardation or amount put into storage averaged 74,000 c.f.s. This spread over the area of 45,310 sq. miles is equivalent to a rise of 0.53 ft.

The precise extent to which each of several causes contributed to this effect is uncertain. It may in part have been caused by dredging and in part by scour in some of the outlet channels, induced by the churning of the propellers of deeply laden boats. It is probable that on rare occasions noteworthy scouring by the swift current of the river-bed has occurred beneath deep ice-gorges.

6. Permanent lowering of not exceeding 6 inches has been caused by diversions of water through canals. The Chicago Drainage Canal has lowered each of the lakes, except Superior, by about five and one-half inches, while the Welland Canal and the Erie Canal have contributed to the lowering of Lake Erie, and slightly to Lakes Huron and Michigan.

7. Lake Superior has been raised by the closing of control gates at its outlet, in operation since 1916. It has been stated that by means of this regulation its elevation during the recent general low water period has been maintained a foot or more higher than otherwise possible. This has temporarily lowered the other lakes by withholding water that would otherwise have flowed into them.

   The diagram on page 52 showing the remarkably small natural yield of Lake Superior in the past few years is of great interest in this connection.

8. Lake Ontario has been raised by about six inches for the benefit of navigation, by the construction of the Gut Dam in the Galop Rapids by the Canadian Government. The level of the St. Lawrence River near the head of the Canadian canal around the Long Sault has been raised a foot or more by the construction of a temporary dam across the South Sault by the Aluminum Company of America for the purpose of increasing its diversion of water for power and increased output during the world war.

MOMENTARY CHANGES IN LAKE LEVELS

Momentary changes in elevation of surface occur in addition to the above eight kinds of changes which affect the monthly averages of lake elevation. These brief changes balance and disappear in the process of averaging. Among them are the almost continuous wave oscillations of the water surfaces, caused by wind, which rise and fall through a height varying from a mere ripple to several feet and follow one another at intervals of one or two seconds of time.

These momentary fluctuations do not affect the automatic recording gauges by which lake levels are measured, because these gages are set within "stillboxes" which are carefully designed to shield the gage from these waves and to give an average of the fluctuating momentary levels in the lake.

The effects of long continued winds and of barometric seiches are mostly balanced in the records of monthly averages by the location of gages near both ends of each lake and at intermediate harbors, but in the case of Lake Erie the greater prevalence of winds from the west is believed by Mr. W. T. Blunt to slightly increase the average elevation at Buffalo.

ALLOWANCE FOR EARTH-TILT

In all of these studies of lake levels through a long period of years, and in planning for the future, the large progressive changes in apparent level caused by earth-tilt, at Chicago, Toledo, Sandusky and Toronto, also at Port Arthur and around Georgian Bay, should always be taken into account.

If, as seems almost certain, the low shores, the harbor bottoms, the drainage and sewerage outfalls into the lake are sinking at Chicago, Toledo, Sandusky, Toronto, etc., at **the rate of a foot per century, relative to lake levels,** this is highly important. Also it is important to reckon upon the probable shoaling in St. Marys River, at the lower lock sills at the Sault Ste. Marie, and in the harbors at Port Arthur, and around Georgian Bay, **at a rate of more than one foot per century.**

MEASURING THE LOWERING OF LAKES BY DIVERSIONS

Relation of Lake Elevation to Discharge

Before the Chicago Canal was completed, the engineers of the U. S. Lake Survey had estimated accurately that a diversion of 4,333 cu. ft. per sec. would, in course of time, cause a lowering of about 2¾ inches in each lake except Superior.

It seems desirable that this record should make plain in non-technical language, that **there is no possibility for error in the statement that the total lowering of lake levels caused by the diversion of 10,000 cubic feet per second, through the Chicago sanitary canal, does not exceed six inches,** also it is desirable that this record show how the lowering caused by diversions through the Chicago, Welland and Erie Canals has been measured.

The height at which each lake stands depends on the rate of discharge, in cubic feet per second, over the permanent bed of its outlet. Obviously, when copious rains give more water to be discharged, the lake rises. When a year of small rainfall gives a smaller quantity to be discharged the lake level naturally falls. When water is taken out through another outlet, like the canal at Chicago, also, obviously, lake levels must fall. The question is, what is the most accurate means of measuring the fall that will result from any stated diversion.

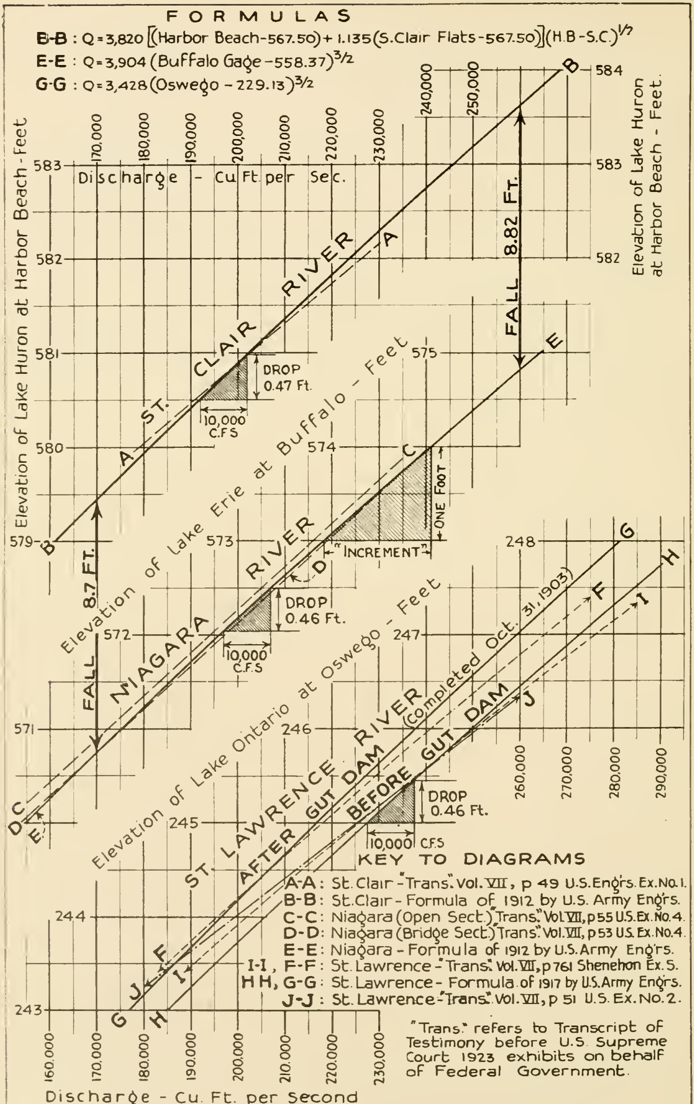
The most accurate means of estimating the amount of lowering of each lake that will be caused by diversion of any stated quantity, is found in the discharge diagram for that lake. Copies of these, on a small scale, are given on pages 30 to 36, and on page 212. Each discharge diagram is the result of a large number of extremely precise current-meter measurements made simultaneously with measurements of height in lake. By means of many repetitions, and by a selection of observations made under most favorable conditions, series of measurements have been obtained at each lake outlet corresponding to various stages of height in the lake.

After having obtained a series of accurate discharge measurements at various heights of the lake the discharge diagram for each lake is constructed by plotting on co-ordinate paper to a large scale, each complete measurement of discharge at the corresponding height of lake, and drawing a line averaging these observations. This relation of discharge to elevation has also been expressed in formulas, the constants in which have been adjusted with all practicable precision by the method of least squares.

The diagram on page 30 shows these separate measurements that have been made in the Niagara River and their remarkable agreement, and the accuracy with which the relation of lake height to quantity discharged has been established.

The conditions having been carefully chosen so as to cover the greatest practicable range of heights in the lake, this line will show the rate of discharge from the lake for any given elevation of its surface, for ice-free conditions, and will also **show the rate of decrease in lake height, corresponding to any stated lessening of discharge.**

Discharge diagrams in the simplest form for Lakes Huron, Erie and Ontario are given on the following page. No diagram for discharge of Lake Superior is given here because of the changing conditions introduced by the recent constructions of regulating gates and power plants, moreover Lake Superior is not affected by any of the diversions of water by canals now under discussion.



DISCHARGE DIAGRAMS FOR OUTLETS OF LAKES HURON-ERIE-ONTARIO.

INCREMENTS OF DISCHARGE

The so-called "increment," or increase in discharge in cubic feet per second for one foot increase in elevation at high, low and mean stages, was found in recent years, or about the year 1900, to be as in the following table. It has not been possible to determine the increment for the Lake Huron outlet so precisely as for Lake Erie.

The curve of discharge on each diagram is so nearly a straight line that the increment may for many practical purposes be considered constant from highest to lowest stages.

"Decrements" rather than increments are what we now have to consider in relation to canal diversion, but the word "Increment" is a time-honored term in the Lake Survey and obviously values are precisely the same whether measured up or down.

TABLE OF INCREMENTS FOR EACH LAKE

	Increment For High Stages	Increment For Low Stages	Increment For Mean Stages
At the outlet of Lake Huron	20,000 c.f.s.	18,400 c.f.s.	19,200 c.f.s.
At the outlet of Lake Erie	23,000 "	20,600 "	21,800 "
At the outlet of Lake Ontario	23,700 "	21,600 "	22,700 "

The elevations adopted by the U. S. Army Engineers, from many years of observation at standard average stages for the several lakes, in classifying the above increments and used as the basis in estimating effects of diversions for Huron, Erie and Ontario, are as follows: (See Warren Report, p. 375.)

	Low	Mean	High	Range
For Lake Superior	600.7	602.3	604.1	3.4
For Lake Michigan & Lake Huron	579.6	581.1	582.6	3.0
For Lake Erie	570.8	572.3	573.8	3.0
For Lake Ontario	244.5	246.0	247.5	3.0

That each lake sometimes rises much higher and sometimes falls much lower than these nominal "high" and "low" stages, may be seen from inspecting the diagram of monthly lake elevations following page 198.

It seems to be accidental that these values of the increments for the different lakes are so nearly alike. From this fact of nearly equal increments in Huron, Erie and Ontario (which is confirmed by many observations while establishing the formulas of discharge), it necessarily follows that all of these lakes move very nearly in parallel, in their changes of elevation from year to year, assuming that uniform climatic conditions prevail over the entire Great Lakes region. In other words, unless discharge is held back by ice gorges, the same conditions of large rainfall that raise Michigan and Huron one foot also will raise Erie and Ontario almost precisely one foot.

Also, it follows from this equality of the increments that the diversion of any stated quantity from Lake Michigan will lower all of the Great Lakes, except Superior, by very nearly the same amount.

COMPUTATION OF AMOUNT OF LOWERING CAUSED BY A STATED DIVERSION

If at a mean stage of Lake Erie, for example, the elevation would be 1.00 ft. lower for a discharge diminished by 21,800 cubic feet per second; then by simple proportion the taking away of 10,000 cubic feet per second would lower Erie, by proportion.

$$\frac{10{,}000 \text{ c.f.s.}}{21{,}800 \text{ c.f.s.}} \times 1.0 \text{ ft.} = 0.46 \text{ ft. or } 5.56 \text{ inches}$$

If figured for the present stage of low lake levels following several years of abnormally small rainfall, the lowering of the lake caused by diverting 10,000 c.f.s. would be

$$\frac{10{,}000 \text{ c.f.s.}}{20{,}600 \text{ c.f.s.}} \times 1.0 \text{ ft.} = 0.48 \text{ ft. or } 5.82 \text{ inches}$$

The following results, for a stated amount of diversion, can be computed from the increment as in the preceding example, or can be taken directly off the accompanying discharge diagrams.

It is found that taking away 10,000 c.f.s., by the Chicago Canal, at a mean stage of each lake, after sufficient time for re-adjustment,

Will lower Lake Huron	0.462 ft.	equivalent	to	5.544	inches
Will lower Lake Erie	0.463 ft.	"	"	5.556	"
Will lower Lake Ontario	0.467 ft.	"	"	5.604	"

Since each discharge diagram is the mean of a great number of independent measurements, it appears from studying their general concurrence, and the precision with which the measurements of elevation and discharge of each of the Great Lakes have been made, that **no possibility exists of an error of more than about one-half inch, in estimating the ultimate amount of lowering of either one of the Great Lakes that would be caused by abstracting any such quantity as 4,000 or 10,000 cubic feet per second.**

COMPARISON OF LAKE LEVELS BEFORE AND AFTER CHICAGO DIVERSION

One obvious way for judging of the amount by which the Chicago Sanitary Canal diversion has lowered the lakes is by comparing the average of all available records of lake elevation, before and after the canal was built and thus finding out how much lower lakes Michigan-Huron, Erie and Ontario have averaged in the 25 years since the canal was opened than in the 40 years before it was opened.

This method is less precise than that just described, but it has a common sense appeal, if only the periods are long enough to eliminate effects of years of abnormal water yield, large or small.

It is at least of interest to find how well history repeats itself in these long term averages of lake elevations.

Observed Range in Elevation of Lakes Due Natural Causes Before and After the Chicago Diversion

Monthly Means for 40 years—1860 to 1899 inclusive
and 25 years—1900 to 1924 inclusive
Feet above Mean Sea Level

Lake	Extreme high water of 1838 (per charts)	Extreme High Water BEFORE in 40 yrs. 1860 to 1899 incl. Feet	Extreme High Water AFTER in 25 yrs. 1900 to 1924 incl. Feet	Extreme H. W. was Lower in second period by Feet	Proposed limits of Regulation in Navigation seasons	Extreme Low Water BEFORE in 40 yrs. 1860 to 1899 incl. Feet	Extreme Low Water AFTER in 25 yrs. 1900 to 1924 incl. Feet	Extreme L. W. was Lower in second period by Feet
Superior	605.32	604.08 Sept. '69	603.81 Sept. '16	0.27	High–Low 604.5–602.0	600.75 Mar. '80	600.54 Apr. '11	0.21
Michigan-Huron	584.69	583.57 June '86	581.98 June '18	1.59	583.5–581.0	578.98 Dec. '95	578.54 Jan. '24	0.44
Erie	575.11	574.52 June '76	574.03 Apr. '13	0.49	574.5–573.0	570.70 Nov.'95	570.63 Feb. '02	0.07
Ontario	248.98	248.95 May '70	248.62 June '08	0.33	248.5–246.0	243.41 Nov. '95	244.28 Nov. '01	higher 0.87

Although Lake Superior, being upstream from the Sault and 20 ft. higher than Lake Michigan, cannot possibly be affected by the Chicago Diversion, its record is included in these comparisons for the purpose of exhibiting effect of climatic change; also because the holding back of water by its regulation works at Sault St. Marie during the latter part of the second period, has caused higher levels in Lake Superior which in turn have caused lower levels in the other lakes.

Comparison of Averages Instead of Extremes

If instead of comparing, as in the table above, the extreme high and extreme low monthly average elevations for the two periods before and after the Chicago diversion, a comparison is made of the average of all daily elevations of lakes throughout each of the two periods, a relation differing slightly from that in the preceding table is found as follows:

Average of Monthly Mean Heights of Each Lake Before and After the Chicago Diversion

Lake	Extreme Range in 65 years Highest to Lowest Monthly Mean	Average for Whole Period 65 Years 1860—1924	Average for Period 40 years Before Jan. 1st 1900	Average for Period 25 years Since Jan. 1st 1900	Change from first to second period
Superior	3.54 ft.	602.26	602.24	602.29	0.05 higher
Michigan-Huron	5.03 "	581.06	581.46	580.41	1.02 lower
Erie	4.45 "	572.49	572.69	572.14	0.55 lower
Ontario	5.54 "	246.13	246.25	245.94	0.31 lower

It will be shown later that the lowering of Michigan-Huron in the second period, due to the deepening of the St. Clair River by earth-tilt, dredging and scour, may have been 0.5 ft. and that since about 1903, Lake Ontario has been raised five or six inches by the Gut Dam.

If we charge 0.50 ft. of the relative lowering of Michigan-Huron in the second period to the deepening of its outlet combined with earth-tilt, and reckon that for the average of the second period the Gut Dam raised Ontario 5 inches, the comparisons by several independent measures of change in lake elevation due to Chicago diversion stand as in the table below.

During this period of 25 years the movement of earth-tilt has lowered the level of Lake Huron 0.15 ft. as measured by the Harbor Beach gage (which is about 60 miles north of the axis drawn through the Lake Huron outlet). Since the standard gage for measuring the level of Lake Erie is close to its outlet at Buffalo, the apparent level of Erie measured by this gage has not been changed by earth-tilt (at Cleveland the earth tilt in 25 years has increased the reading of the lake level gage by 0.24 ft.)

Final Comparison of Observed Lake Heights Before and After the Chicago Diversion

Lake	Lowering since opening Canal				
	By extreme high monthly Averages	By extreme low monthly Averages	Avg. of extremes	By Averages of daily elevations for whole of each period	Avg. of two methods
Michigan-Huron	1.59 ft.	0.44 ft.	1.01 ft.	1.02 ft.	1.01 ft.
Erie	0.49 "	0.07 "	0.28 "	0.55 "	0.41 "
Ontario	0.34 "	higher 0.87 "	higher 0.26 "	0.31 "	0.02 "

Grand average of lowering by comparison of lake heights is 0.48 ft., or 5.76 inches

By the above method of comparisons of elevations actually observed before and after the diversion, the amount of lowering apparently caused by the Chicago diversion is thus found slightly less than 6 inches.

By the more accurate method of direct computation, described in the preceding pages, the final result after five years continuous diversion of 10,000 cu. ft. per sec. would be 5½ inches.

Since the actual average diversion for the whole 25 year period, beginning with about 3,000 c.f.s. in the earliest years and gradually increasing to 9,000 c.f.s. in recent years, has averaged only 6,795 c.f.s., instead of 10,000 c.f.s., one should expect only 3.7 inches of average lowering would be shown by these comparisons of observed lake levels for long periods, before and after.

This agreement (3.7 inches vs. 5.76 inches), by two such entirely different methods of estimation is remarkably good, considering that in all such comparisons of elevation as presented in the second method of comparing levels, the effects of diversions of water upon lake levels are obscured by the much greater changes in lake height, before and after the Chicago Diversion, due to climatic variations and to the uncertain amount of permanent lowering of Lakes Michigan and Huron caused by dredging and scour of shallow places in the St. Clair and Detroit Rivers.

This comparison of extreme and average lake heights, before and after, has value in the records as an **independent proof that since the Chicago Canal was opened, there has been no great permanent change in average of lake levels, from the elevations recorded in the earlier years, amounting to a lowering of more than half a foot.**

It is a matter of record that there were occasions about 100 years ago when the lakes stood as low as at any time during the past two years. (See page 27.)

High Water of 1838

In Report of Secretary of War, 1868–9, p. 982, D. Farrand Henry states in connection with a comparison of gages around the Great Lakes:

"Very fortunately for these comparisons the remarkably high water of 1838 was generally noticed—and on three of the lakes was referred to permanent bench marks. These were at:

Charlotte, Lake Ontario, by Professor Dewey

Cleveland, Lake Erie, by Colonel Whittelsy

Milwaukee, Lake Michigan, by Dr. Lapham.

"We thus have a common plane of reference on three of the lakes and can easily compare them and the others."

SLOW READJUSTMENT

The readjustment of lake elevation due to a given diversion is an exceedingly slow process, and requires many years for its full accomplishment because of the vast area of the lakes and the small proportion of decrease in rate of discharge caused by a small decrease in the elevation of the lake. This lowering of the lake lessens its rate of discharge through its natural outlet very slowly, and to lower either lake six inches, from such a cause, requires 5 or 10 years for completion, or until equilibrium has become established, after which the stated rate of abstraction causes no further lowering.

The cumulative effect year by year, requiring about five years for 91% of final effect, can be readily computed, by the "method of successive approximations," with the aid of discharge diagram, or "increment," and the known area of the lake, but the calculation is tedious.

One of the members of this committee, Mr. Grunsky, has made such a computation and finds that his results, due a constant withdrawal of 10,000 c.f.s., agree substantially with the figures given on page 5,401, Chief Engineer's report of 1900.

Such computation shows that the total lowering, and per cent. of final lowering, of Lakes Michigan and Huron (using a smaller increment than that most recently found), would be at the end of

1st	year	only	0.199 ft.	or	2.39	inches	or	38	per	cent.	of	final
2d	"	"	0.323 ft.	"	3.87	"	"	62	"	"	"	"
3d	"	"	0.400 ft.	"	4.80	"	"	76	"	"	"	"
4th	"	"	0.448 ft.	"	5.37	"	"	85	"	"	"	"
5th	"	"	0.478 ft.	"	5.73	"	"	91	"	"	"	"

The progressive lowering in the later years is extremely slow. About ten years would be required to reach the extreme lowering which could ultimately result from a constant diversion of 10,000 c.f.s.

The ultimate lowering with an average diversion equal to the original allowance of 250,000 cu. ft. per minute, equivalent to 4,167 cu. ft. per second, would be only 2.4 inches.

Finally, it may be accepted as proved beyond all doubt, that **the total lowering caused up to the present time by the actual amount of the Chicago diversion has been only about 5.0 inches,** which is smaller than the amount computed above, because the amounts actually diverted have averaged only 6,795 c.f.s. for the past 25 years, and for 5 years past only 8,674 c.f.s.; which is much less than the 10,000 c.f.s. used in the above computation.

BENEFITS FROM LOWERING LAKES

It must not be forgotten that the lowering of the lakes, while injurious to navigation, is beneficial to other important interests. For example, there are large tracts of low marshy lands around some parts of the lake shores which would be made more valuable by the drainage thus afforded; and it has been stated that many of the smaller, and some of the larger cities on the shores of the lakes and their connecting rivers, would have their problems of drainage and sewerage made less costly by keeping the lakes at the lowest practicable levels. Chicago, more than 50 years ago, met this issue of wetness from high lake levels, by a large increase in the elevation of the grade lines for its streets.

The benefits to navigation and commerce and to water power development, from raising the lake levels, up to at least the limits of high water established by nature in former years, appear to outweigh these possible benefits from lowering the lake levels.

The change to the very highest levels proposed in connection with the designs for regulation works need not be made immediately. Time can be allowed for slow readjustment, and the designs presented in this report are of a type that permits whatever level is found best for all concerned to be established for the immediate future, and permits either a gradual increase, or an abrupt change at any time.

Since these gates and sluices permit any such change at any time, they are for this reason superior to compensation by means of submerged weirs.

Notwithstanding that reasons such as stated above, might make it appear advantageous to fix both the top and bottom limits of reservoir storage at lower elevations than proposed in this report while preserving the same storage range, a long view forward, and a broad horizon, make it plain that **the present designs should provide for the ultimate establishment of storage levels all over the entire chain of the Great Lakes at the very highest levels practicable,** although 10, or 20, or 40 years elapse before these high levels are brought into effect.

SEPARATION OF CAUSES OF LOWERING

Within the past few years Lakes Michigan, Huron and Erie have averaged, throughout the year, about two feet lower than seven or eight years ago, and also have averaged from three to four feet below their highest mean annual elevations. This has attracted wide attention and all of this great change has been popularly attributed to the diversion by the Chicago Canal, **which actually has caused only about one-sixth part of the total lowering that has occurred.**

A simple analysis of the recorded elevations of Lakes Michigan and Huron at Milwaukee, shows that during the month of December, 1924, the lakes stood at Elev. 578.47 as compared with an average elevation of 581.47 for the 40 years, 1860 to 1899, indicating a lowering during the 25 years since 1900, of 3 feet, or 36 inches.

These present low stages of Lakes Michigan and Huron are explained by the six different causes stated in the following table, which gives the approximate amount of lowering due to each cause.

In this connection, on turning back to the diagram on page 148, showing the relation of net yield of all of the lakes above Niagara to various observations upon evaporation, the lower diagram of lake yield, which is corrected for drafts from storage and for diversions, shows a most remarkable decline; with a net average yield for the six years, 1919–1924 inclusive, averaging only about 180,000 c.f.s. including the diversions, which is about 27,000 c.f.s. sec. less than the average for past 65 years. The rainfall diagram, page 43, also shows for these recent years about 7 per cent. less than the long term average.

Lowering of Lakes Michigan and Huron caused by climatic changes during the six years, 1919 to 1924

The following analysis of the net water yields above the St. Clair River for the 65-year period, 1860 to 1924, indicates that climatic changes have resulted in a decrease in the water yield, and consequently have lowered the elevation of the lakes.

The average net yield of the 4 lakes above the Niagara River for the 59 years, 1860 to 1918 is	210,400 c.f.s.
The probable average net yield of Lake Erie, 1860 to 1918 is	26,400 "
The resulting net yield of lakes above St. Clair River for the 59 years is	184,000 c.f.s.

For the six years 1919 to 1924, the net yield of the 4 lakes above the Niagara river averages .... 182,800 c.f.s.

And the net yield of Lake Erie for these six years averages 26,700 "

Giving an average net yield of the lakes above the St. Clair River for the period 1919 to 1924, of .... 156,100 c.f.s.

Decrease in average yield above the St. Clair River for the six years 1919 to 1924 from that of the previous 59 years, (184,000–156,100), is .... 27,900 c.f.s.

Indicating a lowering of Lakes Michigan and Huron in the ratio of $\frac{27,900}{21,000}$, or 1.33 feet equivalent to .... 16.0 inches

Assuming that 95% of the total effect has been accomplished, the lowering is equivalent to .... 15.1 inches

As has been explained on previous pages, it takes time for the full effect of a decrease in discharge to be felt on the change in regimen; however, the decrease in yield has been greater in the last two years, amounting to 40,600 c.f.s. in 1923 and 44,700 c.f.s. in 1924, so that it is quite possible that very nearly the total lowering due the average decrease of 27,900 c.f.s. during the six years since 1919, has been effected.

Lowering of Lakes Michigan and Huron caused by Retention of water in Lake Superior by closing its Regulating Gates in recent years

The diagram on page 52 shows that the annual net water yield into Lake Superior during the 6 years since 1918 has averaged 32,200 c.f.s. below the average yield for the previous 59 years, which was 79,000 c.f.s.

This deficiency of net yield into Lake Superior has gradually increased to a maximum of 38,900 c.f.s. in 1924.

This is a reduction in water yield in 1924 of 49%, or nearly one-half from the average of the previous 59 years.

According to the formulas for discharge of Lake Superior in its natural condition before the regulating gates were installed, a lessening of the flow by 32,200 sec. ft. would have corresponded to a lessening of the elevation of the lake amounting to about 1.74 ft. using an increment of 18,500 c.f.s. between elevations 601 and 603 as given in the report on regulation of Lake Erie, 1910, page 53.

But it takes several year's time for this adjustment between lake elevation and discharge.

Since the discharge has been going on at a gradually decreasing rate for 6 years, this regimen would have been nearly attained. From analogy with other lakes one might reasonably expect that the average elevation for the year 1924 would have been lower than the average of the preceding 59 years by, say, 95% of 1.74 or 1.65 feet. This can be computed in detail, although the process is tedious.

As a matter of fact the gage records show that in 1924 the average elevation of the lake was .... 601.42 ft.
Whereas the average of the preceding 59 years was .... 602.29 "
so that the actual lowering was only .... 0.87 "
which when compared with the probable lowering in the absence of gates estimated above as 1.65 ft., indicates that the lake level has been held up by the gates about .... 0.78 ft.
or nearly a foot.

Because of the continual discharge one cannot estimate the lowering of Michigan and Huron, caused by this lowering of Superior, in proportion to their area, which would give a corresponding lowering of only $\frac{31,810}{45,410} \times 0.78 =$ .... 0.55 ft.

Rather must it be estimated in proportion to the respective increments of discharge for the St. Clair River and the St. Mary's River, or in the proportion of $\frac{18,500}{21,000}$, or $0.88 \times 0.78 =$ .... 0.68 ft.
which is equivalent to a lowering of .... 8.2 in.

There has been at the outlet of Huron, as at Lake Superior, 6 years in which the regimen could be established.

This figure of 8.2 in. must not be taken as final, but rather as an outside limit.

In making such a comparison one must not overlook the fact that the yield from all of the lakes seems to have been diminishing as set forth on pages 514 and 515, where it is shown that the outflow from Lake Erie which is the most accurately measured of any, seems to have been diminishing at an average rate of 12% in 70 years, or about 1% in 6 years. Whereas the regulating gates in the St. Marys River were not completed so that complete closure could be made until about 4 years ago.

PROBABLE DISTRIBUTION OF RECENT TOTAL LOWERING OF LAKES MICHIGAN AND HURON

As Compared with the Average Up to 25 Years Ago (or Prior to Opening of Chicago Sanitary Canal)

AMONG THE DIFFERENT CAUSES

(Note that the present extreme lowering is recent—within 6 years since 1918. That in previous low cycles—1911 and 1914–15—the lakes stood within six inches as low as in 1925.)

1. Rainfall, 5% to 10% less than normal. Water yield into lakes by gagings was about 10% to 15% smaller. Possibly larger evaporation contributed. These climatic conditions lowered lakes below normal during 6 years, 1919–1924	probably 15.1 inches
2. Retention by storage in Lake Superior within past 5 years has lowered other lakes during 6 years, 1919–1924	probably 8.2 inches
3. Lessened frequency of ice jams, since 1891 to date	not more than 1.0 inch*
4. Enlargement of outlet channels of Lake Huron by dredging and natural scour (within past 35 years)	perhaps 4.0 inches
5. Earth-tilt has lessened Harbor Beach gage reading within 25 yrs. $\left(\frac{90}{100}\text{ mi. x }\frac{25}{100}\text{ yrs. x 0.63 ft. x 12 in.}\right)$	about 1.7 inches
6. The effect of lowering Lake Erie about 4 inches, by increased diversions of about 6,000 c.f.s. through Welland, Erie and Black Rock Canals, backs up through Detroit and St. Clair Rivers and lowers Huron and Michigan	about 1.0 inch
Total effect of Chicago diversion to date	**5.0 inches**
Total lowering below normal of 25 years ago, from all of the above causes	about 36.0 inches

Thus the effect on elevation of Lakes Michigan-Huron caused by Chicago Canal is 5.0/36.0 or about one-seventh of whole.

The first two items may soon return to normal, and the third may not occur, leaving nearly a foot of permanent lowering.

The regulation works proposed will raise Lakes Huron, Michigan and Erie an average of 2.0 feet above the normal of 25 years ago, and could be made to quickly raise all lakes 3 or 4 feet.

Note that this lowering is 36 inches below what may be called the Normal Elevation under natural regulation.

And that there have been years when the lakes have been above normal elevation, for example: In years of excessive rainfall, and prior to dredging, retention, and recent increases of diversion.

For example, in **1876 and in 1886 the water in Lakes Michigan and Huron stood about 48 inches and 52 inches respectively above their recent height** or about 18 inches and 22 inches respectively, above normal.

A chief purpose of the proposed regulation works is to **forthwith raise the mean annual lake levels about 2½ feet above those prevailing during the past two years, and to prevent them from again falling so low in the future.**

*Counting the peaks which indicate ice-jams before and after the year 1900 in the diagram on page 492 they are found fully as frequent since 1900; but some of the earlier ones as 1886 may have been larger or of longer duration.

VARIATIONS IN DISCHARGE

By means of the broad lake areas and their restricted outlets, nature regulates the discharge of the Niagara and St. Lawrence Rivers to a degree of uniformity that appears marvelous when one analyzes the great variations of discharge of the inflowing streams. When, for example, one takes the measured outflow from Niagara month by month, and adjusts this for the effect of rise or fall of each lake in lessening or increasing this discharge through storage or release of storage, and thus derives the figure for monthly net inflow, month by month, this inflow is found to be extremely irregular even in a year of ordinary rainfall. It represents the averaging of many separate and diverse discharges from tributary rivers which differ greatly in their run-off, as is shown by tables on pages 60 to 64. And when one notes the widely differing effects of evapaoration from mid-winter to mid-summer, or the vast volume poured into a lake in a great rainfall, the general uniformity of outflow is particularly remarkable. The effect of natural regulation is partially shown by the difference between the two mass curves in the diagram on page 373.

The restricted lake outlets at the Sault, at the head of the St. Clair River, and at the head of the Niagara River, all aid greatly in this natural regulation by holding back excessive floods in storage over the vast areas of the lakes, and discharging the flood at a gentle rate.

The effect of natural regulation is shown by the difference between the two mass curves in the lower diagram on page 373, one of which shows a smooth curve of **outflow** at Niagara, as regulated by Nature, while the other—the extremely irregular line—shows the net **inflow** to all of the lakes separated from the storage effect of the rise and fall of each lake.

A review of the records of gage heights in the lakes shows several occasions in which the mean height of Lake Erie has risen more than one foot from the mean height of March to that of April. On one occasion, from March to April 1913, the mean height of Lake Erie rose from elevation 572.45 to 574.03. This rise of 1.58 feet over the 10,470 square miles area of Lakes Erie and St. Clair is of itself equivalent to an average inflow for the whole month at the rate of 175,500 cubic feet per second over and above the outflow during the same period. The rate of inflow at the peak of this flood must have been very much larger. The total inflow, to Lake Erie including that coming from the Lake Huron with that from its own local drainage, averaged nearly 400,000 c.f.s. during this month; but the regulating effect of the rise of level in Lake Erie, held the discharge through the Niagara River down to a maximum rate of about 242,000 c.f.s. Meanwhile, surplus flood water was also being stored and held back in Lakes Huron, Michigan and Superior, and the average gross inflow to all of these lakes as measured by rise of each, amounted in all to nearly 800,000 c.f.s. in excess of the measured outflow of the chain of lakes at Niagara.

On the other hand, there are times when the natural inflow to all of the Great Lakes, including both that from the tributary streams, and that from the rain which falls on the surface, averages for a whole month less than the evaporation from the vast areas of lake surface, leaving no natural run-off whatever for the Niagara River and for the St. Marys River except that which comes from the drawing down of the several lakes.

These wide variations in the net water yield into the lakes, exclusive of storage, are illustrated in Column X of the table for Niagara mass curve computation on page 354; which in the first year of these gagings shows in April 1860 a net water yield from all the drainage areas upstream from Niagara amounting to 552,100 c.f.s., while the actual outflow in the Niagara River during this month was less than half this quantity, or 242,300 c.f.s.

In November of the same year (1860) the outflow, as regulated by Nature, had fallen only to 224,800 c.f.s., although the estimated net inflow to the whole chain of lakes upstream, after allowing for evaporation, had become a negative quantity. In other words, the draft from storage shown by the lowering of all of the lakes, amounted to 2,700 c.f.s. more than the measured outflow.

In the latest year of the record (1924) there are similar extremes shown by the table on page 365. We find by Column X a total net water yield into Lake Erie for the month of May averaging 441,200 c.f.s., of which 230,500, or more than half, is absorbed in storage by raising the levels of the lakes. For the two months, November and December, the sum of the evaporation losses on all of the lakes exceeded the inflow from their tributary streams, so that the actual measured outflow during November of 184,800 second feet, shown by Column I, was provided from the release of storage, by lowering all of the chain of the lakes a weighted average amount of 0.391 feet, which during this month was equivalent to a constant drain at the rate of 365;000 c.f.s., of which a part disappeared in evaporation; so that the net result, while discharging 184,800 c.f.s. at Niagara, as shown by Column X, was a negative yield into all of the lakes at the rate of 166,200 c.f.s., which, of course, simply means that **evaporation was in excess of the total inflow to this extent of 166,200 c.f.s.** which is equivalent to 2.14 inches in depth lost from all the lakes above Niagara.

The depth evaporated in one month, from mid-November to mid-December must have been more than this, because inflow from the tributaries never ceases entirely. In fact, records of inflow give an average for the 4 lakes of 1.13 inches equivalent depth on lake surfaces, which would make the total evaporation equal to 3.27 inches.

Notwithstanding this excellent regulation by nature, as described above, which occasionally is aided by an ice gorge in the St. Clair River, it is not perfect, and it can be improved at relatively small expense, so as to prevent the lake levels falling as low as at present, by about two feet; while also increasing the mean monthly minimum discharge by 10,000 to 20,000 c.f.s.

Variation in Discharge of Lake Erie

It is of interest to note the extent of the present fluctuations in discharge in the Niagara and St. Lawrence Rivers, because **it is the minimum discharge which chiefly limits the amount of primary or permanent power obtainable,** and obviously this minimum can be increased by release of surplus, previously stored in months of larger water-yield, from the drainage areas.

The average value (after correction for retardation by ice) of discharge from Lake Erie) through the Niagara River given in the "Warren Report" p. 258, derived from gage readings of 51 years, 1861 to 1912 inclusive, is 207,000 c.f.s. Long-term averages tend to smooth out and conceal the wide range of the elevation and discharge from month to month and from year to year.

It is of interest to note the increased range of variation found in comparing periods successively shortened in length.

The following table gives the range of height of Lake Erie on the discharge diagram, also excess and average discharge for each of several periods, first taking the figures as they stand in the gage records and without addition to allow for the Chicago diversion, or subtraction to allow for the decrease due to ice-cover or to ice-jams, and later giving the corrected values.

First, the 5-year continuous term, showing the highest average of height and discharge of any within the 65 years of gage records is compared with the 5-year continuous term showing the lowest height and discharge.

Second, the calendar year of largest height and discharge as compared with the year showing the smallest.

Third, the month of largest discharge is compared with the smallest.

RANGE FROM HIGH TO LOW DISCHARGES OF LAKE ERIE

	Range Between 5-Year Continuous Cycles of Largest and Smallest Discharge	Range Between Calendar Years of Largest and Smallest Discharge	Range Between Month of Records of Largest and Smallest Discharge
	c.f.s.	c.f.s.	c.f.s.
Largest average Discharge Date	228,900 1860–1864	236,300 1862	257,700 June 1876
Smallest average Discharge Date	189,300 1895–1899	178,300 1895	166,600 Feb. 1920
Variation	39,600	58,000	89,100
Mean of extremes	209,100	207,300	211,100

The above comparisons become changed after correcting discharge for canal diversions and ice, but not allowing for rise and fall of Lake surfaces to the following figures:

Highest average Discharge	228,600	236,000	256,700
Lowest average Discharge	190,590	179,000	170,900

Making further allowances for rise and fall of lakes within these periods, the figures for net yields into all of the lakes above Niagara, including also the water taken out by canals, becomes as follows:—

Highest average Discharge	208,700	213,600	698,200
Lowest average Discharge	189,000	120,000	84,100

Longer cycles of widely varying yield are shown by the mass curves following page 372.

First comes a cycle of high yield, 1860–1885, cf. .... 216,700 c.f.s.
Then a sudden decrease for 17 years, 1886–1902 to .... 196,300 c.f.s.
Then a recovery during 16 years, 1903–1918 to .... 214,900 c.f.s.
followed by the period of small yield and small discharge which is still in effect.

The average daily discharge in extreme cases is greater than the largest in the table above, but it is stated on page 258 of the "Warren Report" that in the Niagara River immediately above the Falls, (including the water diverted at Niagara for power) **discharges greater than 235,000 c.f.s. or less than 160,000 c.f.s. are very rare, occurring only two or three times a year.**

As an example of greater variation in discharge of Niagara River, due to the piling up of water in the eastern end of Lake Erie by a strong wind from the west or southwest, long continued, and the lowering by the reverse oscillation, we have the case of December 7, 1909.

At the brief peak of this oscillation there was an extreme water elevation at the foot of Lake Erie of..580.28 ft. or about 8 feet above the average.

For this elevation, the diagram gives a nominal discharge of about 400,000 c.f.s. at the head of the Niagara River for less than an hour. The precise amount of the maximum discharge is uncertain, because there was insufficient time for the regimen of flow corresponding to this height to become established along the head of the Niagara River.

As an example in the opposite direction, on February 1, 1915, by the drags of the wind, the water was forced down at the Eastern end of Lake Erie to an elevation at five p. m. of..567.38 ft. which is about 5 feet below the average level.

For this elevation the discharge diagram gives a discharge of only 106,000 c.f.s. at the head of Niagara River.

These extremes of height are for very short periods, at most two hours, and the effect on the discharge is like a flash, or soon gone, and has extremely small proportional effect on the total discharge for 24 hours. The variation in discharge and in elevation twenty miles downstream, near Niagara Falls, during these brief wind effects is only about half as much as at the foot of Lake Erie; because of the regulating effect of the storage in the reservoir formed by the 20 miles of river between, and because of the time required for transmission of the flood wave.

Seasonal Change in Discharge

The average monthly discharge of the Niagara River is commonly greater in June than in January by about 20,000 c. f. s. and the extreme range in the monthly average from low to high within one year (1904) from January to June, was found to be 52,000 c.f.s.

These figures correspond to differences in elevation of about 0.92 ft. and about 2.40 ft., respectively, on the discharge diagram.

The seasonal clogging of lake outlets by ice-jams now serves the needs of navigation to a very noteworthy extent in winters of exceptional severity, by raising slightly the level of the lakes upstream from the obstruction. An excess of height thus gained drains down very slowly, but is too uncertain to be depended on. This service can be much better performed by gates and sluices under human control.

POSSIBILITIES OF LAKE REGULATION

The only practicable method by which the elevations of these lakes can be regulated, is by holding back a portion of the discharge, from one or all of the lakes, by means of gates and sluiceways in a dam extending partly or entirely across the outlet. The lake then can be raised by lessening the discharge, or its elevation can be lowered by increasing the discharge. It is found that the **design of Regulating Works must be governed by practicable elevations** rather than by consideration of variation in quantitites of water-yield, in years of large and small rainfall.

The problem first of all is to find out **what is the greatest practicable range of height for storage purposes,** recognizing that magnitude of flowage damage fixes the high limit, and that needs of navigation fix the low limit, and then find by study of discharges and mass curves, what is the best that can be done with the storage capacity found in all of the lakes between these limits of height, while working toward **making the discharge as nearly uniform as practical conditions will allow.**

The study of lake heights and of quantity of water to be discharged comes first; and the design of works necessary to produce these heights and rates of discharge comes later.

Notwithstanding the vast area of these lakes, the flow cannot be permitted to be made perfectly uniform by means of storage and release, because there is not storage capacity enough between the allowable limits of high water and low water. The practicable range between high water and low water is limited at the top, by injury that might be caused by flowage, if the lakes were allowed to rise too high; and at the bottom, by injury to navigation if the lakes were allowed to be drained too low. Therefore there will be some occasions when water must be wasted from lack of storage and from fear of flowage damage, and at other times it may be necessary to lessen the outflow to prevent loss of depth of loading by the great ore boats.

Gains and losses must be balanced. The regulation works should be designed of such a character as to permit the limits of high and low water to be changed from year to year by the commissioners in charge.

The mean daily flow of the Niagara River, as already stated, within the ordinary year now varies from..............160,000 c.f.s. to 235,000 c.f.s.

And after deducting for present diversions by the Chicago, Welland and Erie Canals now averages, (1900–1924)..............................208,900 c.f.s.

It can be so regulated in the winter months that there need be seldom, if ever, less discharge than........180,000 c.f.s.

Seldom for any long period in the summer, or navigation season, need the discharge be smaller than........190,000 to 200,000 c.f.s.

Or larger than........210,000 c.f.s.

But in seasons of exceptionally heavy rainfall it may be necessary to discharge as much as........250,000 c.f.s. during a period of several consecutive weeks.

In other words there must, on relatively rare occasions, be as much as ....40,000 c.f.s. of surplus yield wasted to prevent certain lakes from rising too high and because of refraining from drawing them so low as to seriously interfere with the depths desirable for navigation.

By thus regulating the discharge, the elevations of water surface in the several lakes can be maintained 2 or 3 ft. higher than the elevations which now prevail in harbors and in restricted channels between the lakes, in low cycles of low rainfall.

And at least........20,000 c.f.s.

Or perhaps at times........50,000 c.f.s.

Can be added to the present minimum discharge of........160,000 c.f.s. for the benefit of power and also of navigation.

The 20,000 c.f.s. thus added to the flow, for development of primary or "firm" power, can add 425,000 horsepower to the firm power obtainable at Niagara under 312 ft. head, and furthermore can be made to add about 300,000 horse power under the 225 ft. head on the St. Lawrence which is awaiting development between Ogdensburg and Montreal; the power in each case being estimated on 75 per cent load factor and 80 per cent over-all efficiency.

In other words, in addition to the gain of 2 to 3 feet in navigable depth, **about three-quarters of a million horse power, of "firm" or "primary" power, can be added in the ultimate development as a direct result of the construction and operation of the proposed regulation works.**

Always it must be kept in view that it is amount of rise and fall, or range in height, through which regulation of discharge has to be obtained, and that if, by reason of fear of flowage damages, lakes cannot be raised to the full height proposed in this report, the same range can be had through dredging the channels deeper, to an extent equal to the reduction in high water plane.

POSSIBLE RANGE OF REGULATION OF HEIGHT

The figures in the following table give the proposed regulated heights, which have been adopted tentatively.

As has been previously stated, the tentative high limit is set from 0.5 ft. to 1.2 ft. below the recorded standard high water of 1838 noted on the U. S. charts of each lake, in order to give a margin of safety. Later investigations possibly may raise or lower these maximum and minimum regulation heights.

The design presented for the works would not be changed in any important particular if one or both of these limits were moved up or down six inches, or a foot, or even two feet. Regulation is a question of range between high and low levels; not one of absolute elevation above mean sea level.

	Maximum Height Recorded on Charts (1838)	Proposed Maximum Regulation Height	Margin of Safety Feet Height	Proposed Minimum Regulation Height	Maximum Storage Range over Series of Years	** Present Minimum Height — Monthly Average	*** Feet Gain in Minimum Depth for Navigation
Superior	605.32	604.5	0.8	602.0	2.5	601.0	1.0
Michigan & Huron	584.69	583.5	1.2	581.0	2.5	578.6	2.4
Erie	575.11*	574.5	0.6	573.0	1.5	570.6	2.4
Ontario	248 98	248.5	0.5	246.0	2.5	244.5	1.5

*The Maximum Heights in Columns Nos. 1 and 2 do not include brief wind-effects or "Seiches" in which the cycle of oscillation is about 3 or 4 hours for Lakes Superior, Michigan and Huron, and about 13 hours for the major cycles on Lake Erie.

**The present Minimum height for a day, or sometimes for a week, is much lower than this monthly mean.

***The average effective depth gained for navigation would be more than this, because each lake would normally be held by the regulation works at a high level for the longest time practicable, and would drop to the Minimum height of the preceding column only near the end of long periods of deficient rainfalls.

In Lake Superior, a partial inspection made by members of this committee near the locks, power plants, and factories at the Soo, indicated that a foot or more could be added to the maximum height proposed above; but a careful reconnaissance all around the shores and harbors of Lake Superior is needed before attempting to say just how much can prudently be added, or how far one could go in expenditures for increased flowage.

At all of the lakes the possibilities for future benefit to both navigation and power development are so vast that liberal expenditure may profitably be made for dikes and for flowage damage. **The raise to the full height now proposed does not have to be made forthwith.** The top foot or half foot may be delayed many years, or can be made by stages or after an interval of several years, while flowage rights are being secured.

The requisite range of 2.5 feet for storage and regulation of discharge can be obtained **either by flowing the lake margins higher or by dredging the channels and harbors deeper.** Which method is the better is largely a question of cost.

One reason for the smaller gain shown for Lake Ontario in the table above, is that the average elevation for Ontario has already been raised about 0.5 foot by the construction of the Gut Dam at the Galops Rapids. The present importance of raising the level is relatively less in Lake Ontario than in Lakes Erie, Huron and Michigan, because of its far smaller total annual tonnage, and because of the present limitation of draft in the Canadian Canals.

It is important to now study the maximum possibilities, and design the works so that the regulating gates can be closed to a small opening and for long periods, so that in the more distant future, or whenever it is found profitable to use it, the water can be thus held back to give greater depth and greater storage.

Whenever demands for more storage in Lake Ontario are created by future power development along the Saint Lawrence River, surveys may show that the maximum limit for regulated height in Lake Ontario can be raised, and this should be considered in the designs for improvement now being made by the International Waterways Commission.

Regarding all proposals to raise lake levels there will, of course, be protests from a hundred localities. Riparian owners around the great government-controlled storage reservoirs on the head waters of the Mississippi, completed more than 25 years ago, are said to still haunt the offices of the engineers in charge, almost every time the waters are raised; and so it goes with storage reservoirs pretty much everywhere. The one man on the shore can not see the benefit to a thousand men one hundred miles away.

Also the problems of management will call for long and patient study and careful adjudications for the greatest good of the greatest number, with adjustment for all actual damage in a liberal and friendly spirit. **Altho the final maximum limit for flowage, for purposes of navigation and for the development of power, may not need to be reached by the waters for 20 years, it should be forseen and provided for from the beginning in designs and in securing flowage rights.**

If so great a height of flowage as herein proposed really proves impracticable after a thorough investigation and definite surveys have been made, then it is possible to achieve substantially the same effect by dredging channels and harbors deeper. The question is, which is cheaper, all things considered.

REGULATION OF DISCHARGE

When the time comes for utilizing these water resources to their utmost, a constant study of climatic conditions, rainfall, temperatures and forecasts, will be required in order to most efficiently operate this scheme of regulation of discharge, so as to obtain greatest practicable uniformity for purposes of power development, along with maintenance of highest practicable depths for navigation, in relation to existing lake levels; because of the natural and artificial limitations to storage height.

For this reason, and for other good reasons, the levels of all 5 lakes should be under comprehensive International control, of efficient executive character, for quick decision, so that in times of ample yield of water from the drainage areas, storage space may be left in anticipation of the probable amount of inflow, and so that at the very beginning of a flood when lakes are full, and the forecast shows a large flood is soon coming, the sluice gates may be opened to give, for example, a discharge of 250,000 c.f.s or 25% above the regulated average discharge from either Lake Huron or Lake Erie; or more if the flood demands it.

Tentative operative schedules, which have been worked out for the cycles of highest and lowest water yield within the past 65 years, show no conditions that cannot be met with entire safety. There will be ample time to study the conditions and time in which to make up new operative schedules, in the years before maximum demands for power arrive.

The general scheme of storage in wet years, and of depletion of storage in dry years, is set forth in the mass curves of the diagrams on pages 373 and 381.

In some years, transfer of surplus can be made from an upper to a lower lake with great advantage; but in general, the controlling climatic conditions are so wide-spread that when the sluices are opened at the outlet of Ontario for the benefit of the St. Lawrence, they must also be opened on the Niagara, St. Clair and St. Marys Rivers. A surplus in Superior can thus be made immediately available in Ontario.

It is proposed that the space between these regulation heights and the maximum historical highwater of 1838, averaging almost precisely one foot in height, be left as a margin of safety for emergencies and as provision for excessive rainfalls or excessive obstruction by ice, such as may come only once or twice in a century.

With storage maintained up to these high levels in years of surplus, the draft for increasing the discharge in a subsequent cycle of small rainfall may be expected to slowly lower these levels in all of the lakes about 2 ft. or 2½ ft., with successive seasonal ups and downs during this long cycle. The gradual release of the large volume stored in 2 ft. or 2½ ft. depth over the vast area of all these lakes, will maintain a much larger discharge than otherwise possible, for power, for scenic effect at Niagara, and for the improvement of navigation in the lower St. Lawrence.

It may be found best to permit less draw-down in one lake than in others. For example, it may be made the rule to hold Lake Erie full to the limiting height until toward the close of the navigation season, or until the season when strong winds are more liable to cause high fluctuations; or, made the rule to permit a draw-down of only one foot in Lake Erie, or to a minimum of El.573.0; while the storage in the other lakes is drawn down about 2.0 or possibly 2.5 feet; thereby obtaining much greater minimum depth than now in the channel between Lake Erie and Lake Huron, and in the Black Rock Canal and Upper Niagara River, with minimum expense for dredging.

The channel in which lack of depth now first restricts depth of loading of the larger boats, is said to be that through Lake St. Clair; and this can be remedied to an important extent by holding Lake Erie at high levels.

Seasonal change in limits probably will also prove useful; as for example, closing the St. Clair gates on October 15th, and drawing down Lake Erie during the winter in anticipation of the high winds of October and November, and also, in order to gain in storage space for the spring floods.

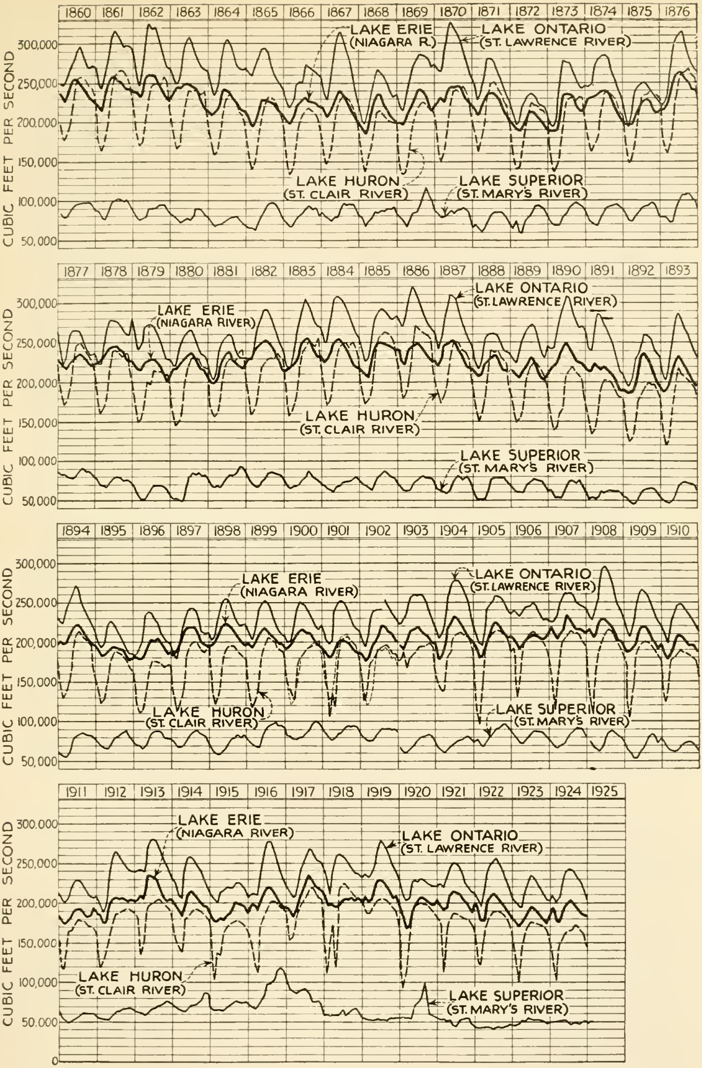
Because of the relatively small area of Lake Erie and its proximity to the Niagara water power developments, some gain in storage can be had without injury to navigation, by partly closing the gates at the outlet of Lake Huron at the close of the navigation season, leaving no more water flowing than the discharge through the open fairway. Lake Erie will then slowly draw down through the winter until replenished by the spring floods coming from its own immediate watershed, and if this is found insufficient for the spring navigation, or for running out ice from the lower end of Lake Erie, in order to give earlier entrance to Buffalo Harbor; the gates in the St. Clair River can be opened wide; whereupon, Lake Erie will soon be raised, because of its small area.

The diagram on Sheet No. 11 of the original drawings for this report, reproduced on a small scale on the opposite page, gives the estimated discharge of all of the Great Lakes, month by month for the past 65 years.

It is particularly instructive in showing that Lakes Huron and Michigan, which by reason of their broad connection in the Straits of Mackinac, are virtually one lake, yield most of the water available for power on the Niagara and St. Lawrence Rivers; and that, according to the gagings, the net water yield, from the drainage area around Lake Erie, is remarkably small. Ontario's drainage area seems to add much more than that of Lake Erie.

This relatively large proportion of the entire water yield measured at Niagara which comes from Lakes Michigan and Huron, emphasizes the necessity of regulation gates at the outlet of Lake Huron. They are doubly important because of the great aiea and consequent great storage capacity of Huron and Michigan per foot in height, and because of the relative small storage capacity of Lake Erie per foot in height.

Also, it is of interest to note the extent to which the outflow from Lake Huron is interrupted in some years and not at all in others. Nature sometimes does much to store water here by means of ice-jams on the St. Clair and Detroit Rivers, to be released for navigation when the ice melts; but in many years this natural ice regulator fails to operate.



AVERAGE MONTHLY OUTFLOW FROM EACH LAKE UNDER NATURAL CONDITIONS

The above values do not include the diversions through the Chicago, Welland and Erie Canals. They are estimated by means of records of height in lakes and the discharge formula or diagram obtained by occasional current meter gagings from 1898 to 1913. The values for St. Clair and St. Lawrence have been corrected approximately for obstruction by ice.

Rates of discharge shown on this diagram prior to 1903 are traced from the diagram published in Report of Chief of Army Engineers, 1903, page 2855.

Subsequent to 1903, values are plotted from tables of estimates received from U. S. Lake Survey office in December, 1924 and March 1925.

Corrections included in these rates of discharge for St. Clair and St. Lawrence Rivers prior to 1903 are understood to have been made for the retarding effect of ice according to the best data available at the time.

For St. Marys River and for the Niagara River, no correction for ice at any time appears to have been applied to the discharge shown by the summer formula. These corrections for ice would have been hardly perceptible in a diagram on this scale.

No correction for diversion at Chicago or into Welland and Erie Canals appears to have been included.

This diagram thus represents the discharge that would have been obtained by direct gauging at each Lake outlet. Data on formulas and methods used in preparing this diagram for the years prior to 1903 are found in Transcript of Testimony of G. S. Williams, pages 217-220, Vol. VII.

Prior to 1903 the values for Niagara in this diagram average about 6,500 c.f.s. (or 3%) higher than those used in the first column of the mass curve computation table in this report.

Prior to 1903 a comparison of discharges for 1900, 1901 and 1902 indicates that diagram values for St. Clair River, average about 5,200 c.f.s., or 3.4% lower in winter, than recent estimates from the U. S. Lake Survey office; partly because of a larger correction for ice having been used in these early years than that later adopted by Engineer Richmond and used since 1903.

The difference in adjustments and corrections before and after 1903 is shown by the two lines for the three years in which estimates overlap, quantities as recently revised by the U. S. Lake Survey being shown dotted.

PURPOSE AND EFFECT OF WORKS PROPOSED

The chief purpose of the structures which the Committee on Lake Levels of the Engineering Board of Review has recommended be built forthwith, and which are to be described more in detail in the present report, is to **control the out-flow from Lakes Michigan and Huron and Lake Erie by means of gates,** so that water can be held back at times of large natural discharge, or during the non-navigation months; and so that this stored water can be released in times of small natural discharge, for providing increased depths for navigation; or for providing increased quantity of water for scenic effect at Niagara; or for increase in water power development at Niagara, or along the St. Lawrence River.

We may anticipate the conclusions on later pages and state here, that by means of the works now proposed, it is found feasible to accomplish at reasonable cost the improvements listed below.

1. A complete remedy will be provided for all lowering of the lakes caused by whatever diversion is permitted at Chicago; be it 4,000 c.f.s. or 10,000 c.f.s.

2. The lakes all can be quickly restored to high levels, within one, or two, or three winters, — the time depending upon the rainfall meanwhile — by closing partially, or completely, all of the gates, from December to March; and by cutting off part of the scenic flow over Niagara Falls at night; without waiting for the recurrence of a cycle of years of abnormally large rainfall or of small evaporation.

3. All of the lakes can be maintained at more than 2 ft. higher elevation than their average for the past 25 years, thus permitting 2 feet deeper loading of boats than is now possible under average conditions.

4. About 20,000 cu. ft. per second (perhaps 30,000 cu. ft.) can be added to the monthly average of low water flow in the Niagara River, and about 75,000 cubic feet per second to its minimum hourly rate of discharge, which, if all used for power, is equivalent to increasing the possibilities for develpment of firm or primary power by about 425,000 horsepower at Niagara, and about 300,000 horsepower on the St. Lawrence.

5. With the aid of the gates and sluices proposed across the Niagara River, about a mile upstream from the Falls, the approach to the Horse Shoe Fall can be unwatered while the deep notch at the apex of the Horseshoe Fall can be filled and levelled up, by means of a small hidden concrete dam, spreading the water again out over the now denuded ends

of the fall so that the progressive erosion at the Horse Shoe Fall can be stopped. It is now eating back in the deep notch at the rate of 7 feet per year.

6. The flow over the American Fall can be increased to its former magnitude, or made larger if concluded desirable.

7. The carrying capacity of the present intake channels to the hydro-electric plants at Niagara, can be largely increased, by the new increase of 5 or 10 feet in depth over their present intakes, particularly that of the new canal on the Canadian side leading from Chippawa to Queenstown.

8. Perhaps double, or even treble the quantity now diverted for power can be taken for that purpose, without injury to the grandeur of the falls, and in fact leave the falls more beautiful than ever before, because much of the water that now passes through the deep notch at the apex of the Horse Shoe is lost to scenic beauty, and creates a mass of spray too large for scenic beauty, which hides a large part of the Horse Shoe Fall. Moreover, the ends of both falls, formerly covered by overflowing water, which have become bare, can be again submerged, thus adding greatly to the grandeur and beauty of the spectacle.

9. All of these regulations can be kept under complete control, and the extent of the regulation changed quickly, within an hour's time; if, and when change is found desirable.

10. A new and much needed international bridge can be provided at Niagara over the piers between the proposed gates; and, if desired, another can be provided over the St. Clair River, or perhaps at the foot of Lake St. Clair.

11. **The extent of Buffalo Harbor can be vastly expanded.**

All of the above can be accomplished within a cost upon which the increased earnings, or lessened cost of freight to the public at large, due to this regulation, will pay such generous interest that the works should be begun forthwith.

The statement of improvements just made will be found supported and explained by the data and the more detailed statements in the following pages.

QUICK RESTORATION OF HIGH LAKE LEVELS

It has been stated above, that by holding back the discharge from Lake Erie and Lake Huron during the winter months when there is no navigation, by means of partially closing the gates in the regulation works proposed in the Niagara and St. Clair Rivers, the present low levels of Lakes Michigan, Huron and Erie could be restored to their former high levels without waiting for the return of a cycle of years of large rainfall.

After the crests of the falls have been repaired and the overflow spread out to the full width, there should be no reasonable objection to partially closing the Niagara River control gates at night, so as to still more rapidly restore the depleted lake levels. For the remote future also, when the power resources of these great rivers have become fully utilized, it will thus be possible to conserve the natural resources by discharging a thinner sheet over the falls after dark.

The repair of the crest of the Horse Shoe Fall, by filling the deep notch in its crest, will permit the temporary holding back of discharge without injury to scenic beauty; and the benefits to navigation, between Duluth and Buffalo, and at the entrance to the Welland Canal, probably will outweigh any temporary loss of depth in the St. Lawrence River.

If, for example, an average of say 50,000 c.f.s., or 25 per cent of the whole flow is held back at Niagara and St. Clair, this will raise Erie 2 feet within 4.5 months and subsequently raise Michigan, Huron a foot within 9.7 months; which may be better business than waiting, say, 7 years for the return of the peak of the cycle of heavy rainfalls, according to the natural slow course of the cycles of years from low lake levels to high, shown by the history of lake levels in the past 75 years.

After the levels of the Great Lakes have once been restored, the plan of operation would be to maintain their elevations continuously at or near the highest levels which prevailed heretofore in years of large rainfall, by means of careful operation of the gates, under international control.

Whenever extraordinary conditions arise producing small discharge, such that the maintaining of the Niagara River flow the at 180,000 c.f.s. would result in drawing down any lake to below the minimum lake levels stated in table on page 230, it is proposed that preference be given to the requirements of navigation, rather than those of power development.

APPORTIONMENT OF BENEFITS

Depths vs. Discharge and Navigation vs. Power

Over about half the height of the proposed new range of lake elevations, navigation and power both are helped; but over the other half of the total possible range in height, the two interests are opposed.

Navigation calls for increased depth of channels. Power calls for greater uniformity of discharge.

The greater depth of channel which navigation calls for, **can be most economically satisfied by deepening at the top,** by raising the water level, instead of at the bottom by dredging.

Power development soon will call for greater quantity of water at times when the natural discharge is small, which can be best obtained by means of control of lake levels for storage.

The designs here presented have been worked out so as to fairly divide the profits, produced by the operation of these regulation works, between improved facilities for navigation, and increased flow for power development at times of small natural discharge.

No change in the structure, but merely a change in rules for opening the gates and sluices, will be required for changing this sub-division between greater depth for navigation and greater storage for power, at any future time.

VALUE OF REGULATION OF DISCHARGE FROM THE GREAT LAKES TO POWER DEVELOPMENT AND NAVIGATION ON THE ST. LAWRENCE

The complete development of the potential four million horsepower of St. Lawrence power, although a popular subject for discussion and for engineering estimates, can not become a fact until some profitable use can be found for such vast quantities of electrical energy, and it may take 50 years to develop this demand.

Nevertheless, it is certain that a much larger development of St. Lawrence power than the total now found at the Cedars, Massena, Lachine, etc., is sure to come within 10 or 20 years and the complete development is so certain to come sooner or later that the works now to be planned for regulating the levels and the discharges of the Great Lakes should take full account of this ultimate development.

No other place in the world presents such opportunities for electro-chemical industries close beside great pathways of commerce, or for cheap power for the thousand uses of industry and the household which are now developing from year to year with marvelous rapidity for a populus region within easy reach. Whenever needs accumulate such that a block of 200,000 horsepower can be marketed at a profit, development is sure to come, and some of those most familiar with the needs of Ontario and central New York believe the time for one such large step forward in this development of St. Lawrence Power is already here.

The proposed regulating works at the outlet of each lake will, each and all, contribute in a very material degree to an economical development of St. Lawrence power, by making the flow of the river more uniform, so that nearly the entire output can be rated as primary power, with all the additional value per kilowatt hour that pertains to primary in comparison to secondary power.

But one does not have to look forward to the future development of St. Lawrence power in order to justify the construction of the regulating works proposed at the outlets of Lakes Erie and Huron. Liberal rates of interest upon the cost of all the regulation works proposed in this report, on the Niagara and St. Clair Rivers, will be recovered from the date when they are put into use, in lessened costs of transportation of coal and ore alone; and the public will get the benefit indirectly if not directly. Therefore, questions of the exhaustion, 40 years or 20 years hence, of the great ore deposits which furnish the great bulk of the present traffic, have no proper place in this discussion. Long before that time comes, the proposed regulating works will have repaid their cost may times over. Beyond the great value to navigation the improvement in scenic value of Niagara Falls would be certain and immediate, and the added value to hydro-electric development is sure to come in course of time.

NAVIGATION IN THE ST. LAWRENCE

Whatever form is taken by future developments and increased depth between the Great Lakes and Montreal Harbor, whether to 25 feet or to 30 feet, for lake carriers or for ocean carriers, for Canadian or for American deep waterways, these regulating works now proposed to be built in the St. Clair and Niagara Rivers will all contribute to its success. Moreover the present navigation canals along side the rapids in the St. Lawrence will be aided in their maintanance of full depth by the greater discharge and therefor the greater depths at the several lock entrances, larger than those which have prevailed in the low water for the past year.

A CHANGING VIEWPOINT

A great increase in the usefulness to mankind, of the waters of the Great Lakes, first became possible 25 or 30 years ago, with the invention of improved methods of generating and transmitting power by electricity.

Development of this kind along the Niagara and St. Lawrence Rivers during these 25 or 30 years, has gone forward step by step with little or no popular appreciation or understanding at any one time of where the next ten years of progress might lead. Now, after 25 years of marvelous progress, we stand nearer to the beginning than to the end.

In other words, up to the present time there has been developed less than one-fourth of the amount of power along these two rivers, that a half century hence is likely to see put to use.

Two of the most notable steps in this great development were:

First, the transmission of power generated at Niagara Falls to Buffalo and to other points of large demand, twenty miles or more distant from the Falls; and

Second, the recent development at Queenstown on the Canadian side, by which about one-twentieth part of the whole Niagara flow is used under substantially the whole fall between Lakes Erie and Ontario, and the power transmitted westward to within half a mile of the business center of Detroit and eastward to points beyond Toronto, around the western end of Lake Ontario, and to municipalities far to the north.

Intermediate steps of great importance have been the development of great water powers along the St. Lawrence in the United States at Massena, and in Canada at the Cedars Rapids. Today, after all of the great developments at Niagara, Massena and The Cedars, the call for still more hydro-electric power from the Niagara and the St. Lawrence is more urgent than ever before, and under the developments of public service regulation by the government, the great benefit comes more to the average citizen than to the non-resident capitalist.

The outlook as to the highest use to which lake levels and lake discharge can be put for the benefit of the inhabitants of the United States and Canada has thus been greatly changed within the past ten or twenty years, from that under which the laws and customs for controlling these Great Lakes and St. Lawrence waterways were developed, at which time the control and use of these waters for navigation was paramount.

Heretofore, the public officials having charge of the maintenance and improvement of these water courses, have had improvements for navigation in view as the foremost and principal responsibility entrusted to them; but henceforth the conservation and promotion of water power development is of equal importance, and may in time come to overshadow in economic value the use of these waters for navigation to the last possible foot or two of depth of draft.

While the outlook of the public upon the relative importance of aids to navigation and aids to electrical power development has changed to some extent, particularly on the Canadian side, it is plain to those in contact with public sentiment, and to those in close contact with the marvelous increase now going on in the applications of electricty to comfort, convenience and economy in the household as well as in industry, that **the changes for the next 25 years are likely to be still more important than those of the past 25 years,** and to tend continually toward greater consideration being given to conservation of water of the Great Lakes for power development.

The writer happens to have had much personal contact with these problems as consulting engineer to various power developments and industrial structures along the Niagara and St. Lawrence Rivers and elsewhere in the United States and Canada, and for 25 years has been noting the marvellous rapidity and forward trend of this development **which is going on faster today than ever before.** Therefore, in planning these regulating works he has made a most earnest effort to fairly and justly apportion between navigation and power, the great benefits obtainable through regulation, and to **give to power development its proper share.**

The proposed structures themselves are made flexible, so that the proportioning between navigation and power can be always in the hands of the international commission, and subject to change at any future time.

THE MAXIMUM POSSIBILITIES OF REGULATION

Plainly the time now has arrived when the structures needed for both compensation and regulation should be planned and built of largest capacity that the natural conditions warrant, although their maximum capacity for control, by closing or opening of gates, may not need exercising until many years later.

There are now available excellent daily records of the heights of each lake for 70 years and many measurements of the discharge of each of the great rivers which forms the outlet to a great lake. Other less complete records of lake elevations extend back more than a hundred years and from these elevations we can compute the discharge with a good degree of accuracy, except for the brief times when the outlets are choked more or less with ice.

After critically reviewing these data on lake levels and lake discharges, the causes of variation, the conditions and precision of measurements, it appears plain that all of the varied conditions of flood and drought, of rainfall, of evaporation, of ice-gorges, etc., that are likely to occur within the next century have already happened and been recorded. In brief it is certain that **there is now no need to wait for more data upon lake levels or upon lake discharge before working out by painstaking computations the extent of control which will give the maximum benefits to both navigation and electric power development.**

The one field in which data are fewer than desirable is that of surveys all around the margins of all the lakes for showing clearly the obstacles to even a greater increase in height for storage purposes than that which is proposed in this report.

However, the margin of uncertainty in the elevations which it is desirable not to go above, or not to go below, in years respectively of greatest flood and of greatest drought can hardly be so great as one foot, and probably is smaller than six inches; and, after sundry preliminary trials it has been found practicable to so design these works that without appreciable increase in cost of structure their gates can be set, changed and regulated at whatever range of heights shall in the future be found most advantageous, be this more or less than that indicated upon the drawings; and **it would cost relatively little to add one foot to the height of either one of these controls,** as shown on the drawings presented herewith, and probably it would be true economy to thus mark them all up.

Moreover, the rules to be formulated under international control for operating these regulation works can be changed from time to time.

ABOUT MAXIMUM HIGH WATER

For many years past all of the charts issued by the U. S. Lake Survey office for the benefit of navigators and others have contained an entry recording the high water of the year 1838. It would seem that this had been done for the useful purpose of serving notice upon all parties concerned that the lakes might again return to these high levels from natural causes, or might be held up to these levels by artificial regulation. (**See note on page 217.**)

In working out the designs now to be described, the writer has estimated upon holding the high water by regulation at elevations from six inches to one foot lower than this recorded high water of 1838, in order that these present estimates should contain some margin of safety against a widespread and long continued rainfall of unprecedented depth, or against other conceivable events which rarely if ever happen. Also sluiceways are provided with surplus capacity of discharge for emergencies, thus giving a double factor of safety against extraordinary large rainfalls, and in addition to this a carefully studied program of operation is planned, under which sluiceways would be opened wide, long before the safe limit of height was reached.

In the distant future, after water ways have been deepened to the sea, it is planned that the present narrow outlets of Lake Huron and of Lake Erie will be also enlarged, thus giving greater capacity than now, for the quick discharge of an unprecedented flood.

In the earlier years of regulation the lakes may be regulated at maximum elevations somewhat less than provided for ultimately in the designs.

In case a detailed reconnaisance followed by a precise survey shows obstacles to the high water limits proposed, rules can be made by the proposed International Lake Control Board, by which the high limit can be at first set low and later gradually raised. It is even possible that the precise survey of elevations of lake margins would show it ultimately profitable to, in extreme cases, go somewhat beyond the standard of high water of 1838, and pay damages where necessary for increased flowage rights.

The Committee on Lake Levels were advised by legal counsel that so far as the American Government has jurisdiction, it is free to maintain lake levels anywhere within the range of height covered by records of height found to have occurred from natural causes, and that if riparian owners have been misled by the low lake levels prevailing for several years past into building structures on the foreshore which will be injured by a return to these higher lake levels produced by natural conditions in the past, they have done so at their own risk.

The writer is not informed as to laws or conditions prevailing on the Canadian shores as to limitation of height of flowage, but if comprehensive and thorough surveys should reveal possibilities of damage it probably would be found that the benefits to the public at large would far outweigh the sum total of the injury caused by higher levels, and that flowage damages might well be adjusted and paid in a generous spirit rather than forego the gain to commerce and industry possible through higher levels.

One of the most important investigations of maximum possible height of flowage needed is that all around the shores of Lake St. Clair, for the purpose of learning about the the practicability of placing the regulating works for Lakes Huron and Michigan at the foot of Lake St. Clair instead of near St. Clair City, as shown on the drawings.

It is obvious that **the farther downstream the regulating works the greater will be the length of river that receives the benefit of increased depth without dredging.**

This matter of flowage damages around Lake St. Clair requires careful consideration, and balancing against cost of dredging of channels through the lake, convenience of new international highway bridge at Windmill Point, etc.

The writer now has no data on the extreme elevations to which Lake St. Clair has been raised by ice gorges, or otherwise, in comparison with the elevation required above the gates, in connection with the proposed open fairway, for regulating Lake Huron at height proposed. One of the chief reasons for the tentative location at St. Clair as shown in the drawings, was that this is near the down stream limit of high banks along the St. Clair River; another was that the river is here of ample width to permit closing by cofferdams nearly one-half of the river, while the other half remains open and of ample width for passing commerce.

Once more the writer desires to make it plain, that the degree of regulation herein proposed for the distant future, can be had by either of two methods,

(1) **By maintenance of lakes at the highest levels of the past (leaving a margin of safety for the exceptional flood that comes once in 100 years), or**

(2) **By fixing the planes of "normal high" and "normal low" water each a foot lower and dredging channels each a foot deeper.**

LAKE SUPERIOR REGULATION

Lake Superior stands naturally at about 20 feet higher elevation than Lake Michigan and thus is removed from all possibility of being affected in height by diversion through the Chicago Canal.

Works for regulating the discharge from Lake Superior and thereby controlling the mean elevation of the lake, have been in use at its outlet for several years past. These comprise a series of Stoney gates extending entirely across the channel of the St. Marys River between the navigation locks on the American shore and the locks on the Canadian shore.

By closing or opening these gates the outflow can be held back, or regulated so as to retain at all times sufficient depth in the navigation channels, meanwhile conserving the head and the discharge for use by the turbines of the large hydro-electric plants and paper mills, carbide works and steel works, located near by, on the American and Canadian shores. These water power plants together are said to use about 43,000 cubic feet per second. This is about 60 per cent of the mean discharge from Lake Superior, which averages about 75,000 c.f.s. in a long term of years. It would seem there was opportunity here for a much larger development of power and for maintaining higher mean levels in the lake.

The Warren Report states (page 18) that since 1860 the lake has fluctuated 3.6 feet in average monthly height, or from 600.50 to 604.10 feet above sea level, while the extremes of daily range are greater; and that the regulating works are obviously beneficial to navigation as well as to power development, and that these works have maintained steadiness and increase of depth.

It is now proposed that by means of these existing works, Lake Superior should be in future regulated in proper relation with Lakes Michigan, Huron and Erie, and ultimately with Ontario, all under the same small international committee of engineers. The committee should be small, for executive efficiency; and international because of the varied interests to be cared for on both sides. Ordinarily, after the whole system has once been adjusted, when gates are opened or closed for regulation of discharge from Ontario, there should be a corresponding regulation at Lake Superior in order to get the best results. Water stored in Lake Superior can in effect be passed along for the immediate relief of conditions in Ontario or in the St. Lawrence River, although the actual water released at the Sault Ste. Marie might require several years for its passage through the lakes. Conditions affecting the yield of water by the several lakes, such as rainfall, temperature, wind movement and evaporation commonly are wide-spread, but not always the same from Superior to Ontario, therefore the regulation should be flexible.

Adding to the present head works at Sault Ste. Marie so as to permit holding the water level in Lake Superior at one, two, or even three feet greater height than is permitted by the elevation of the upstream walls to the present locks, should be thoroughly investigated.

So far as the immediate neighborhood of the Sault is concerned, the changes necessary for holding water higher could be made at relatively small expense. One or two feet more of storage over the vast area of Lake Superior, to be filled in the cycle of large rainfall, and held in storage (meanwhile helping the harbor and channel depths) for perhaps five or ten years, until needed all along downstream in years of small rainfall, would have a large value.

The historical maximum high water of 1838 stated on the Navigation Charts for Lake Superior is elevation 605.32 ft. above mean sea level, which is 1.3 ft. higher than any elevation shown in the diagram of monthly average heights since 1861 and is 1.7 ft. higher than the present maximum regulated height of 603.6 quoted above from the Warren Report. Perhaps nature then had temporary regulation works in service, in form of an ice jam in St. Marys River as well as in the St. Clair River.

One of the first steps toward such increased flowage would be a reconnaisance all around the shores of Lake Superior, in the United States and in Canada, for determining the highest elevation practicable and the damages that should be paid for flowage rights to that level.

The top foot or foot and a half will not be strongly needed for perhaps 40 years to come for power development, and compound interest must be figured for the interval. The point the writer would again urge is plain for the ultimate in the program of the immediate future. The demand for power is coming much faster than most people realize, and sooner or later, all will be needed.

LAKE ONTARIO REGULATION

No designs are now presented for regulation works at the outlet of Lake Ontario similar to those proposed at the outlet of Lake Erie and of Lake Huron, because of the comprehensive investigations and the preparation of designs for larger locks, deeper channels and great water power developments along the St. Lawrence River, all now in progress under an international commission.

By means of the structures along the St. Lawrence River now under consideration, by this International Commission it is proposed to provide channels of 25 ft. or 30 ft. navigable depth all of the way from the Atlantic Ocean to Lake Superior, permitting the passage of grain boats from Great Lakes ports to Trans-Atlantic ports, while also providing for a water power development at perhaps three or four of the rapids between Lake Ontario and Montreal.

What should be done for regulating the elevation and discharge of Lake Ontario is very much "in the air," pending the perfecting of these plans for this combination of slack-water navigation and power development all along the St. Lawrence River by a series of dams. Probably one of these dams will back the water into Lake Ontario and relieve all necessity of regulating works at the Galops Rapids.

How the level of one of the Great Lakes may be raised by an obstruction located far downstream in the river forming its outlet, is well illustrated by the effect upon the level of Lake Ontario caused by the building of the Gut Dam, some years ago, near the head of the Galops Rapids a few miles downstream from Ogdensburg. It is reported this raised the level of Lake Ontario permanently by about six inches although the head of the river is 69 miles upstream with a fall of 1.7 feet in the river between.

The Committee on Lake Levels briefly inspected conditions on both sides of the Galops Rapids, and inspected the Gut Dam from a distance. All conditions were found favorable for building in this vicinity works of whatever type is found desirable, at moderate cost.

These works in their cheapest form, might consist of a dike or crude rock-fill and earth dam, similar to that built across the Gut, or similar to that built across the South Sault just downstream from the intake to the Massena hydro-electric works. Such a dike would raise Lake Ontario **but would not permit using it as a controlled storage reservoir for feeding the St. Lawrence and increasing its flow in time of low water.**

A submerged dike or narrowing the river by a fixed dam is not so perfect a structure for controlling the elevation of Lake Ontario as future conditions and future public interests are certain to demand.

In this connection also it may be of interest to mention a report made to this Committee while on its tour of inspection, that the level of the St. Lawrence River near the entrance to the Cornwall Canal at the head of the Long Sault Rapids was raised about 1 or 1½ ft. by the building of the temporary diversion dam across the South Sault, just below the entrance to the Massena power Canal, several miles away on the opposite side of the river.

PREVIOUS PROPOSALS FOR REGULATION

Regulating the elevation of surface of the Great Lakes, has been under active discussion in many quarters for more than 25 years, and many reports and references to this matter have been published. Naturally the later reports repeat much that was in the earlier reports. The earlier reports, particularly those of the U. S. Lake Survey and those of various waterways commissions were concerned almost solely with the improvement of navigation, and related almost solely to regulation of lake **elevations.**

The question of regulation of **discharge,** as distinguished from regulation of levels, has within twenty years become of great importance; because of the great developments of water power, present and prospective, along the Niagara and St. Lawrence Rivers.

Also, the preservation of the scenic beauty of Niagara Falls has become of great and widespread national interest, and for these and other reasons there are great differences in the proposals of the earlier and the later reports.

A large amount of information bearing on these matters is given in the successive annual reports of the U. S. Chief of Engineers, largely in the Division relating to the U. S. Lake Survey.

The report of the Chief of Engineers for 1904, Appendix EEE, pages 4057 to 4132, bears on this question of regulation and presents some very instructive diagrams showing the remarkably close relation of monthly average lake height to average total monthly rainfall on each of the Great Lakes, as determined from averages for each calendar month 1883 to 1898 inclusive. It is through this natural rise and fall—first a period of accumulation, and later a period discharge—that the Great Lakes exert their present great influence in making the discharges of the outflowing streams, the Niagara and the St. Lawrence Rivers, far more nearly uniform throughout the year than the discharge of any other great rivers of the world.

Also, a large amount of information is contained in the printed "Transcript of Record of the Case of the Chicago Sanitary Canal," and its plan for the diversion of more than 4167 c.f.s. from Lake Michigan, before the Supreme Court of the United States, October Term, 1923. This "Transcript" comprises nine volumes, and 5360 pages of arguments and testimony, chiefly that presented in 1913. There has been much change in view-point during the past 12 years, or since that testimony was taken, because of the great increase in the demand for electrical power.

The Deep Waterways Board in 1896 instituted its careful measurements of discharge in its relations to elevation, chiefly as a preparation of data for its designs for regulating the elevation of Lake Erie, by a dam with gates and sluices to be located at the head of the Niagara River; but at the time of their report, 25 years ago, the possibilities of transmission of water power by electricity, had hardly begun to be realized, and they gave it no attention in their report.

The Engineers of the Chicago Sanitary District have collected and published many data and reports dealing particularly with the Sanitary Canal and the effect of its diversion in lowering the lakes. One of the most interesting of these reports by engineers employed by Chicago interests, is that which bears the date of September, 1919, on the Regulation of the Niagara and St. Lawrence Rivers by Mr. Francis C. Shenehon, Consulting Engineer; formerly principal U. S. Assistant Engineer in charge of Surveys and Gagings on the Niagara and St. Lawrence Rivers.

Mr. Shenehon appears to have been one of the very first to have clear vision of the great gains to both commerce and industry that would be made possible from conserving the storage capacity of the lakes, and "budgeting the waters," as he calls it, so as to bring the greatest benefits to all.

It is extremely significant as showing the change in viewpoint within the 25 years during which studies of regulation have been in progress, that **water power was hardly considered at all in the extremely thorough report of the Board of Engineers on Deep Waterways in the year 1900.**

THE 1921 WARREN REPORT ON RESTORATION OF LAKE LEVELS, ETC.

The latest among many reports from the office of the Chief of Engineers, U. S. Army, and the foremost among all in completeness of data useful in the present discussion, is the so-called "Warren Report," published in 1921, on "Diversion of water from the Great Lakes," to which many references have been made in the preceding pages. This was made to the U. S. Congress, through the Secretary of War, by the Chief of Engineers and the Board of Engineers for Rivers and Harbors.

This "Warren Report" comprises four hundred and fifteen closely printed pages, with many maps, photographs and diagrams, and a wealth of general information, from which there is space in this report for only brief extracts comprising important data. While the present writer has reviewed all other data that he could find in print, he has in general accepted the figures presented by Mr. W. S. Richmond, U. S. Asst. Engineer, as conclusive because of internal evidence of the painstaking character of his review.

With all of its excellence of data and historical references, this report of Colonel Warren, and the supplementary report of U. S. Asst. Engineer Richmond, **presented no definite plan for regulating the elevation or the discharge of the Great Lakes as a whole.**

The Board of Engineers for Rivers and Harbors in reviewing the reports of Col. Warren and Mr. Richmond, went further and proposed gates at the outlet of Lake Erie for the further benefits of power and navigation, and provided for compensating weirs in the outlet of Lake Huron sufficient to remedy the lowering caused by the abstraction of water at Chicago.

The Board of Engineers for Rivers and Harbors states that by means of regulating gates only, at the outlet of Lake Erie, that the flow in the Niagara River can be held between 180,000 c.f.s. and 200,000 c.f.s., with present diversions continued. No computations are presented showing how this can be done without the disturbance of depth for navigation in Lakes Erie and Ontario.

It plainly states that these regulation works at the outlet of Erie are predicated on the expected construction of regulation works on the outlet of Lake Ontario.

Because of the relatively small area of Lake Erie, the utmost effect of operating these gates at its outlet, **obviously could do much less in providing uniform discharge than a plan which includes increased storage depth and regulation of discharge from over the vastly greater area of Lakes Huron and Michigan.** Nevertheless, the Board stated that by the proper manipulation of these gates, the flow of the Niagara River could be made nearly constant, between 180,000 and 200,000 c.f.s. and that this increase of the low discharge would greatly benefit the scenic beauty of the falls.

In 1920 this Board on Rivers and Harbors proposed that this dam at the outlet of Lake Erie should hold it at a more nearly uniform level than now during the season of navigation; probably between elevations 573 and 574; thereby increasing low water depths on the lake by perhaps one and one-half feet; while its range of oscillations during the open season for navigation might be reduced to a foot or less (excepting those oscillations caused by wind).

Obviously, also, the low water depths of all the channels connecting with Lakes Huron and Erie would be improved by this raising of Lake Erie, and its effect would reach back through the Detroit and St. Clair Rivers so as to largely compensate for the lowering caused by the Chicago Diversion, pending the completion of the regulation works in the Saint Clair River.

PREVIOUS STUDIES FOR REGULATING LAKE ERIE

These comprise principally:

(1) Extensive surveys, water gagings and designs for works at the outlet of Lake Erie by the Board of Engineers for Deep Waterways, reported in 1900.

(2) A remarkably complete review of records of water elevations and discharges of all of the Great Lakes, with estimates of results from a dam at outlet of Lake Erie, by the International Waterways Commission, reported in 1910.

(3) Further studies under the same commission, and recommendations for compensating weirs above the Power Intakes near Niagara Falls, reported in 1913.

(4) Various studies by Mr. F. C. Shenehon, reported in 1919, 1924 and 1925.

(5) New studies and recommendations for a dam with regulating sluices at the outlet of Lake Erie, by the Board of Engineers for Rivers and Harbors, described in the Warren Report of 1921.

The regulation of Lake Erie has been the subject of more studies than that of all of the other lakes, but the control of its outlet still remains as in the state of nature; largely because the site for gates and sluices, most strongly urged heretofore, has been in the head of the Niagara River, close to the City of Buffalo. Those deeply interested in Buffalo and its commerce have feared that gates at the outlet of Lake Erie might add to the obstruction of Buffalo Harbor by ice; still further delaying its opening in spring, which is now about two weeks later than at Cleveland. This delay is said to be caused by the collection during the late winter of large masses of floating ice upon the broad, shallow reefs of rock at the lower end of the lake.

Obviously, any possibility of adding an obstruction to rapidly running out enough of this ice to open a clear passage way for shipping, is undesirable; but, on the other hand, there appear to be possibilities of so designing and placing breakwaters at the head of the river and the harbor entrance that **most of this ice could be held to rot in the lake and give earlier opening of the harbor than heretofore.**

Moreover, by opening the quick working sluices now proposed to be located 20 miles downstream from Buffalo just above the falls, a swift current for running out ice from the main channel all of the way down from Lake Erie could be quickly brought into action.

Also, there has been a popular but mistaken belief that the open head of the Niagara River serves to an important extent as a safety valve for the relief of high lake levels at Buffalo, during the brief high water following a long strong wind.

Another important reason for this 25 years of inactivity is found in the fact that the regulation of the levels of **Lake Erie alone** was proposed, without much regard to regulating works at other lake outlets, and it was found that to regulate Lake Erie alone to any important extent, would greatly disturb relations in Lake Ontario.

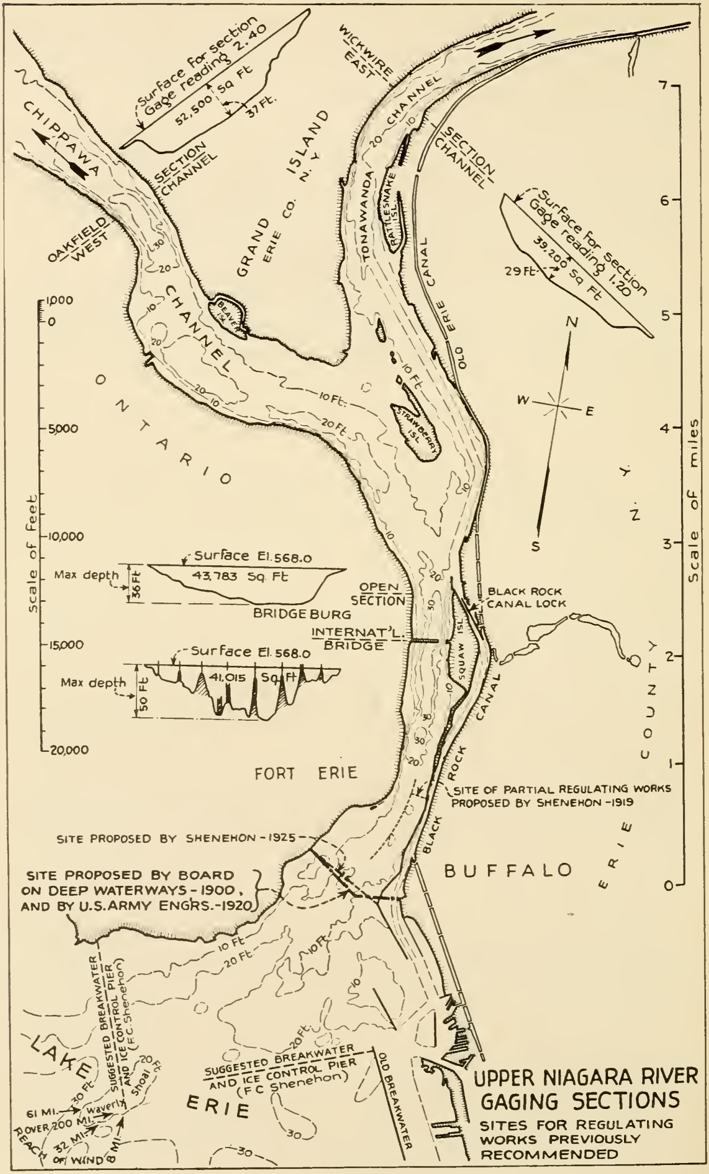
Still another important reason has been that until the review of the Warren Report by the Board of Engineers for Rivers and Harbors in the year 1921, the studies were devoted almost wholly to the **regulation of elevation, without much attention to regulation of discharge.**

THE DEEP WATERWAYS REPORT OF 1896

This was made pursuant to an act of Congress, introduced February 8, 1895, by Senator William F. Vilas, authorizing a preliminary inquiry concerning deep waterways between the ocean and the Great Lakes, and providing commissioners therefor. This became a law on March 2, 1895; and on November 4, the President appointed James B. Angell, President of the University of Michigan, John E. Russell, former governor of Massachusetts, Lyman E. Cooley, of Chicago, an eminent engineer, all of whom served without compensation, and met for conference with a similar commission appointed by the Canadian Government, but reported separately.

This American commission was assisted in many ways by engineers of the United States Engineer office and compiled a vast amount of valuable information, on which basis they recommended the surveys of, and preparation of definite designs and estimates of cost for, the most promising routes.

In brief, their report of 263 pages and 26 sheets of maps and statistical diagrams, laid the foundation for the appointment of the Commission of Engineers, which prepared the report of 1900.


UPPER NIAGARA RIVER
GAGING SECTIONS
SITES FOR REGULATING WORKS PREVIOUSLY RECOMMENDED
Surface for section Gage reading 2.40
52,500 Sq Ft
37 Ft.
SECTION CHANNEL
CHIPPAWA
OAKFIELD WEST
WICKWIRE EAST
CHANNEL
GRAND ISLAND N.Y.
ERIE CO.
BEAVER ISL
TONAWANDA
RATTLESNAKE ISL
CHANNEL
SECTION CHANNEL
Surface for section Gage reading 1.20
39,200 Sq Ft
29 Ft
ERIE CANAL
OLD
STRAWBERRY ISL
ONTARIO
N
S
W
E
N. Y.
Scale of feet
1,000
0
5,000
10,000
15,000
20,000
Scale of miles
Surface El. 568.0
Max depth
36 Ft
43,783 Sq. Ft
BRIDGEBURG
OPEN SECTION
BLACK ROCK CANAL LOCK
INTERNAT'L. BRIDGE
SQUAW ISL
Surface El. 568.0
Max depth
50 Ft
41,015 Sq. Ft
BLACK ROCK CANAL
ERIE COUNTY
FORT ERIE
SITE OF PARTIAL REGULATING WORKS PROPOSED BY SHENEHON - 1919
SITE PROPOSED BY SHENEHON - 1925
BUFFALO
SITE PROPOSED BY BOARD ON DEEP WATERWAYS - 1900, AND BY U.S. ARMY ENGRS. - 1920
SUGGESTED BREAKWATER
SUGGESTED BREAKWATER AND ICE CONTROL PIER (F.C. Shenehon)
LAKE
ERIE
SUGGESTED BREAKWATER AND ICE CONTROL PIER (F C Shenehon)
OLD BREAKWATER
Shoal
Waverly
61 MI.
OVER 200 MI.
32 MI.
8 MI.
REACH OF WIND

DEEP WATERWAYS REPORT OF 1900

In June 1900 the U. S. Board of Engineers on Deep Waterways proposed large Stoney gate sluices across the head of Niagara River, by which Lake Erie was to be maintained at elevation 574.7 above mean tide in New York Harbor (by revised levels of 1903) and expressed the opinion that during the navigating season Lake Erie could be held within 0.6 ft. of this high water. This report of 25 years ago, it will be noted, proposed raising the normal level of Lake Erie to 0.2 ft. greater height than that proposed in the present report.

This Board comprised Major C. W. Raymond, Mr. Alfred Noble and Mr. George Y. Wisner, all engineers of outstanding experience and ability. Its report covered remarkably thorough surveys, careful studies of choice of route, and designs for structures for ship channels of 21 ft. and 25 ft. depth, from Lake Ontario by two different routes; all within American territory, one from Lake Ontario by way of Oswego and Oneida Lake to the Hudson River at Albany, N. Y., and the other ran down the St. Lawrence River nearly to Messina and thence a cut across, through land all in American territory, to Lake Champlain and thence southerly into the Hudson River. This report comprises 1115 pages of d scriptive text, in two large volumes, and in addition, a large portfolio of outline maps and designs for principal structures. It comprised careful estimates of cost, by each route, but at unit prices about half of those of today.

The feature in this Deep Waterways Report now of chief interest is its plan for the regulation of the elevation of **Lake Erie at the high level of 574.7 by Stoney gates and sluices located near Buffalo,** or near the end of the lake and at the head of the Niagara River. Since all who knew the late Alfred Noble have high respect for his sound judgment, it is of interest to note here that Mr. E. E. Haskell who had an important share in those studies, has stated to the writer that Mr. Noble's part did not cover the location of these structures at the head of the river, and that although he took an important part in the design of the stoney gates, he expressed misgivings about the outlet of the lake being the best place for them.

No studies of methods or works for controlling any other lake than Erie appear in this report of 1900, and no comprehensive plan was then given for doing more than **keeping Lake Erie full at a high stage,** and studying what the effect of doing this would be on the Niagara River, Lake Ontario, and the St. Lawrence River.

At that time, **twenty-five years ago, regulation of elevation was almost the only consideration; regulation of discharge for power was of no such importance as today.**

INTERNATIONAL WATERWAYS REPORT ON REGULATION OF LAKE ERIE

In 1910 the first International Waterways Board was appointed in accordance with an Act of Congress, which after establishing an International Commission defined one of its duties as follows:

> "That said Commission shall advise on the feasibility of locating a dam at the outlet of Lake Erie with a view to determining whether such dam will benefit navigation, etc."

This Commission was composed of General O. H. Ernst, Mr. George Clinton, and Mr. E. E. Haskell, in its American section; and of Mr. Geo. C. Gibbons, Mr. Louis Coste, and Mr. Wm. J. Stewart in its Canadian section.

After studying over again much the same data as previously available, but making more extended computations upon the effect of rigorously regulating the levels of Erie alone, by gates **only at outlet of Lake Erie,** and studying the effect of thus controlling the discharge of Lake Erie upon the levels of Lake Ontario and the discharge of the Niagara and St. Lawrence Rivers, this International Board of 1910 came to diametrically opposite conclusions from the Deep Waterways Board of 1900, in that it recommended that no dam be placed at the outlet of Lake Erie, because of ice troubles that might follow; and because of loss of the safety-valve effect found in the state of nature for relieving a sudden rise in Erie caused by wind; and because of undesirable effects on the elevation and discharge of Lake Ontario.

It is of interest to note that the words of the Act of Congress specified the location of the regulating dam which they were to investigate was to be **"a dam at the outlet"** of the lake. Thus they were hardly free to propose a dam with gates and sluices at the site 20 miles down river and downstream from the entrance to the power canals and a mile above Niagara Falls, as proposed in the present report.

In this 1910 report there were presented elaborate tables and diagrams for various schemes of regulation chiefly directed to the improvement of navigation, and to what could be done in maintaining high levels in Lake Erie. **Little or no attention was given to the possibilities of regulating the entire system of lakes as a whole** so as to give the most uniform discharge practicable, or to the great benefit to the public of providing more water power, by means of storage of the surplus yield of wet years to be released in years of small discharge.

Three years later, after further study of the levels, cross sections and hydraulic gradients between the outlet of the lake and the head of

Niagara Falls, a committee of the same Board unanimously recommended a submerged weir across the Niagara River, about 20 miles downstream, and **just upstream from** the water power intakes.

This was located upstream rather than downstream from these intakes, where it would have helped the water power developments, in order to prevent lowering the upper Niagara River by further diversions by the power plants.

The idea of designing structures so that they would aid both power development and navigation, seems to have not arrived.

1913 Report of International Deep Waterways Committee

The recommendation for a weir quoted in the preceding paragraphs is found in the 1913 Report of the International Waterways Commission, comprised in Senate Document 118 of the 63d Congress, Second Session. This commission was still composed of the same membership as in 1910.

This report was prepared by a committee of the International Board composed of Mr. E. E. Haskell, and Mr. Wm. J. Stewart and was concurred in unanimously by the whole commission. Mr. Haskell was then Dean of Engineering in Cornell University, and for many years previous had been U. S. Assistant Engineer in charge of many of the investigations made by the U. S. Government upon the regulations of the Great Lakes. The Canadian Commissioner, Mr. Wm. J. Stewart, also was an engineer of large experience in these matters.

This report was supplementary to the earlier report on the Regulation of Lake Erie, made in 1910, described on the preceding page, and completed the development, on paper, of a project that had been considered in 1910, but which could not be worked out at that time, because of insufficient data.

After new surveys and new gages, set by precise levelling all along from Lake Erie to the Falls, and careful investigation and review of previous studies for the regulation of Lake Erie—Messrs. Haskell and Stewart presented this design, consisting of a deeply submerged **compensating weir,** to be built across the Niagara River within the Chippawa Pool, just **upstream from the present Canadian and American power intakes,** by which the level of the Chippawa Pool at stage of mean flow would be raised about three feet. This weir was designed of such shape that at high stages it would present no important obstruction to discharge.

The Engineers prepared profiles for various stages of the natural water surface along the upper Niagara River which showed that the fall of 10 ft. from Lake Erie to the Chippawa Pool occurred mostly in the upper three or four miles, and they computed typical elevations of the backwater surface of Niagara River from point to point up into Lake Erie for these typical profiles, and found that the proposed weir would have a back-water effect reaching up to these rapids in the upper three miles of the river, but that the back-water effect within the rapids would diminish rapidly upstream toward their head, so that the estimated rise above normal caused by this weir at mean stages would raise Lake Erie about 0.39 ft.; or from elevation 572.6 to elevation 573.0; and would increase its extreme low water stage from El. 570.0 to El. 570.51, while it increased the extreme flood stage to the almost imperceptible amount of 0.11 ft. or from El. 579.18 to El. 579.29.

These profile data shown on pages 123 and 124 of their report, have been utilized in the studies presented later in this report for computing the backwater effects of the designs having dam and sluices located about a mile upstream from the falls.

This weir proposed 20 miles downstream from the outlet of Lake Erie in 1913 was immovable and **permitted no regulation of the discharge and no regulation of lake elevation** to meet varying climatic conditions. It merely remedied the lowering of Lake Erie, caused by the diversion through Chicago, Welland and Erie Canals and prevented a further lowering being caused by power diversion at Niagara.

Being located upstream from the power intakes it was to be a structure for defence of navigation against effects of encroachment by the water power companies **instead of a means for helping both navigation and power.**

The outlook at Niagara has greatly changed in the twelve years since this recommendation for a submerged weir was made, largely by reason of the remarkably successful developments and wide distribution of power by the Hydro-Commission of Ontario and by the great enlargement of the American plants and by the present strong demand for additional power.

Gates at Lake Erie Outlet Proposed by Mr. Shenehon

In 1919 the Consulting Engineer of the Chicago Sanitary District—Mr. F. C. Shenehon—who for many years previously had been an important member of the engineering staff charged with surveys and discharge measurements in the Niagara River, presented designs for an elaborate and novel sluiceway structure extending about half way across the head of the Niagara River, and comprising gates by which the discharge could be partially controlled. These gates were incorporated in a novel design of floating caisson, which was in summer to be floated into position between massive permanent piers and later removed and again floated to a safe anchorage near the shore during the winter season in order to lessen obstruction by ice, thus **losing all opportunity for winter storage in Lake Erie** by means of these regulating gates. Obviously all power for regulation and adjustment of discharge under this project of Mr. Shenehon would be removed during the non-navigation season.

The location for these regulation works chosen by Mr. Shenehon was about a mile downstream from the site chosen by the Deep Waterways Board of 1900. (Both sites are shown on the preceding map.)

In comprised gates and sluiceways extending **only half across** the river, in combination with a submerged diversion wall running nearly a mile up and downstream a little east of the middle of the river and just east of the present channel for light draft ships through these rapids, which have about 4 feet fall.

In October 1924, Mr. Shenehon again brought this design forward in his paper before the Detroit meeting of the American Society of Civil Engineers on the regulation of the Niagara and St. Lawrence Rivers, and in addition to gates near the outlet of Lake Erie he now proposed a submerged weir below the "Dead Line" and **below** the main power canal inlets, a mile above Niagara Falls, for increasing the height in the Chippawa Pool.

In December 1924, while the present Board of Review was at work on these problems, Mr. Shenehon presented another modification of his plan for regulation works located at the head of the Niagara River.

Works for Regulating Outflow from Lake Erie Proposed in 1920 by Board of Engineers for Rivers and Harbors

On August 24, 1920, the Board of Engineers for Rivers and Harbors of the U. S. Army Engineers reported (pages 45 and 46 of the Warren Report): that because of the public sentiment in favor of opening the upper St. Lawrence to large vessels, etc., further study had been given to the regulation of Lake Erie and after much consideration they recommended a regulating dam at the head of the Niagara River, close to the site selected by the Deep Waterways Board of 1900.

These works were to extend entirely across the head of the Niagara River. They estimated their cost at about eight million dollars. The Board suggested that this cost should be defrayed by Canada and the United States upon such basis as might be agreed to. They did not publish the plans. A reason suggested for this omission is that because of the works being of an international character it was felt that the Canadian Government should participate in their design.

NEW CONDITIONS CALL FOR NEW DESIGNS

As has been stated above, conditions have changed greatly in the fourteen years since the report of the International Waterways Board in 1910 which recommended there be no dam at the outlet of Lake Erie and no attempt to regulate its discharge. Some of these new conditions are:

1. The demand by the lake carriers for deeper draft.
2. The growing importance of hydro-electric power.
3. The demand for deeper channels between the Great Lakes harbors and the Atlantic Ocean, open to ships that cross the Atlantic.
4. The fact that extensive power development in the upper St Lawrence River, will necessitate dams and sluiceways by which the elevation of Lake Ontario can be controlled, thereby making it practicable to prevent injurious disturbance of Ontario's levels by regulating the discharge of Lake Erie alone.
5. The awakening to the necessities of the prevention of the erosion and gradual self-destruction of Niagara Falls.
6. The realization that the Falls now lose much of scenic effect by the waste of water through the deep notch near the apex of the Horse Shoe Fall, which might be spread out over the now denuded ends by a concrete dam which would level up this notch in the natural crest, and spread the surplus water in a thin sheet out over the now bare rock at both ends of the Horseshoe. This dam itself need cost but little more than $100,000 after the present channel has been laid bare, and should be built of irregular exterior, resembling natural rock in shape, altho it would be hidden beneath the overflowing water.
7. The recent successful completion of the Chippewa-Kingston Canal for the Canadian "Hydro" has removed some of the difficulties mentioned in the International Report of 1913, which then affected the location of a dam in the Niagara River.

PRESERVATION OF NIAGARA FALLS

The Shenehon Report

The preservation of Niagara Falls has long been an object of solicitude by scientists and engineers familiar with all of the conditions, and on June 29, 1906, Congress directed that surveys be made under the supervision of the U. S. Army Engineers and made an appropriation of funds for this purpose in connection with studies of diversion of water for power. A progress report by Major Charles W. Kellar, bearing date of Nov. 30, 1908, endorsed by the Chief of Engineers giving results of surveys, comprising 173 pages including many maps, tables, and photographs, was published in August, 1911. Senate Document 105, 62d Congress, First Session. Mr. C. F. Shenehon was Principal Assistant Engineer in charge. Mr. Sherman Moore, C. E. was his principal assistant. These surveys were made chiefly in 1906–07 and 08.

This report also contains, in pages 23 to 33, an excellent description of the gagings of the flow in the head of the Niagara River and of the precautions taken to insure extreme accuracy.

This report of 1911 was largely of the nature of beginning the collecting of precise information upon which studies for preservation could be based and was pioneer work of an uncommonly profound character. It gave results of water gagings, measurements of velocity and depth, and extensive new surveys of the approaches to Niagara Falls. It gave a large amount of new data on contours of the ledge immediately above the falls, many measurements of velocity of water approaching the falls, measurements of the amounts of water diverted by the power companies, and photographs of the falls with various quantities of water flowing over, but the author stopped short of making any very definite recommendations of methods for preserving the falls from continued erosion and cutting back of the crest.

At that time, Mr. Shenehon and Major Kellar seem to have contemplated chiefly preservation from the impairment of scenic effect by diversions for power, but their investigations led the way toward further surveys, completed about 10 years later, which considered providing a remedy for the slow self destruction by erosion in the deep gap at the apex of the Horse Shoe Fall.

On page 15 of the printed report of Major Kellar there is buried the inconspicuous, but significant, statement — "The **damage already done** and that which may be expected **from further diversions** . . . may be . . . remedied by **a submerged dam** placed in the bed of the river **immediately above** the Horse Shoe Fall." The progressive impairment of scenic effect that had been going on for 10 years caused by diversion for power was checked soon after this report by international agreement, and limitation of the quantity of water permitted to be diverted, but **progressive impairment by erosion remained unchecked.**

THE 1920 REPORT ON PRESERVATION OF NIAGARA FALLS

The Board of Engineers for Rivers and Harbors on page 47 of their report dated August 24, 1920 upon Diversion of Water from the Great Lakes and Niagara River, also recommended works immediately upstream from the Horse Shoe Fall for its preservation and for increasing its scenic beauty **by a better distribution of the water over its whole width.**

The proposed works comprised the construction of a submerged weir about 250 feet upstream from the crest of the Horse Shoe Fall and an excavation of top of ledge near the easterly end of the crest so as to give a more uniform distribution of water. A rough submerged weir was recommended to extend out westerly from the head of Goat Island toward the Canadian side so as to direct more water over the American Fall, and thus restore its scenic beauty, which appeared to have been impaired by the diversions for power.

In brief, the Board concurred in the recommendations made by Lieutenant Albert B. Jones, who had been detailed by the Chief of Engineers to make a thorough study of this matter of preserving the scenic beauty of the Falls. The works for the preservation of the Falls planned by Lieutenant Jones and will be described briefly below.

The Board recommended that this work be not attempted until after regulating gates had been built at the outlet of Lake Erie, by which the volume discharging over the Falls could be partially controlled by holding back water in storage in Lake Erie.

It was estimated that all of this work at the falls with its cofferdams, two submerged weirs, one close to the Fall and another near the head of Goat Island, excavation of ledge, etc., would cost about an additional six million dollars, which added to the eight million dollars for sluice gates at the head of Niagara River made a total expenditure of about $14,000,000 proposed within the Niagara River by the U. S. Army Engineers Board on Rivers and Harbors in 1920 for the regulation of Lake Erie and the preservation of Niagara.

Proposed Site of Regulating Works and Bridge

AIRPLANE VIEW OF NIAGARA FALLS
Showing Relative Position of Proposed Regulating Works and Bridge

LIEUTENANT JONES' REPORT OF 1920 ON WORKS FOR PRESERVATION OF NIAGARA FALLS

The collection of data necessary to designs for the preservation of the Falls begun by Mr. Shenehon was continued under First Lieutenant Albert B. Jones as a part of his studies, and presented as Appendix C, to the Warren Report, pages 253 to 284, but Lieutenant Jones went much beyond the collection of data and presented definite designs for the repair and preservation of Niagara Falls. His report dated August 26, 1919, comprises about 32 pages of descriptive text and 22 photographs of the Falls selected to show present conditions at various stages of flow and **forms the best treatise that has ever been published upon the progressive self destruction of Niagara Falls,** and the methods by which a practicable remedy could be provided. Also he set forth methods for greatly improving the scenic grandeur of both the American and the Canadian Falls by restoring the flow of water over their now denuded ends.

The investigations by Lieutenant Jones, as well as many previous observations, prove that Niagara Falls are certainly suffering deterioration by reason of the erosion of the bed rock, principally at the apex of the Canadian or Horse Shoe Fall.

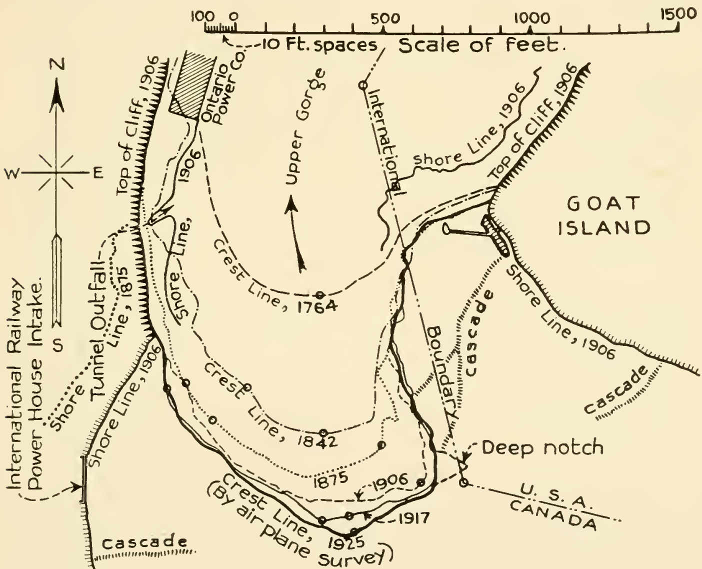
The place in the crest of the Horse Shoe Fall, where injury is greatest, now known as "The Deep Notch," is on the American side of the International Boundary. The situation, and the rate of recession, are shown in the map which follows.

There is abundant historical evidence as to the recession of the general line of the crest of the Horse Shoe Fall within the past fifty years, and ample evidence that this recession is progressing mainly by the undermining of soft strata underlying the crest **by the abnormally heavy current at the apex of the Horse Shoe Fall.** The present rate of recession at the apex seems to be determined with certainty. For 160 years it has averaged 4 to 6 ft. per year, but in recent years has cut back much more rapidly. For the past year the recession, as measured by triangulation and by an airplane survey, is said to have been 7 feet at the apex. The deep notch at the apex is taking such shape that **the injury becomes progressively more serious.** The flow through the notch is of small scenic value.

Lieutenant Jones says, "As matters now stand there flows over the central 600 feet of the Horse Shoe Fall, a volume of approximately 80,000 c.f.s., which not only **is entirely wasted** in that it creates neither scenery or power, but which is actually a detriment in that it is the cause of the destructive action."

Also he says: "The recession is causing a decided decrease in the beauty of the Horse Shoe Fall." Both ends of the shelf of rock over which the Horse Shoe Fall is precipitated are becoming uncovered and the width of the Fall made less, largely because of the large proportion of the entire discharge which is carried in this deep notch at the apex.

About 415 feet in length along the original westerly end of the Horse Shoe Fall, having become denuded of water flowing over, has been covered by a wall, begun soon after 1887. Within the memory of men now living, water flowed over the crest beneath this wall on top of which visitors now stand.



PROGRESSIVE EROSION OF HORSE SHOE FALL

Table rock, once a conspicuous feature at the Canadian end of the Falls, has become only a tradition.

The recent effect of the recession has been to **concentrate the volume of water near the apex and leave the ends of the Falls bare.** Meanwhile the cloud of mist has been increased and the view of the most sublime part of the spectacle has become obscured by this high, broad and dense cloud of mist.

The diversions for power also have seriously impaired the grandeur of the Horse Shoe Fall. Lieutenant Jones presents photographs showing quantities flowing corresponding to the average conditions of former and later years and says: "In the face of these photographs, any contention that the beauty of the cataract has not been seriously affected becomes ridiculous."

As a matter of fact, the original average discharge over the American and Canadian Falls was 207,000 cu. ft. per sec. The diversions for power have taken away 50,000 cu. ft. sec. or nearly ¼ of the whole. **In spite of this diversion it is possible by a relatively small amount of engineering construction to make the Falls more beautiful and more grand than at any time within the past 100 years.**

It has long been obvious to many observers that the scenic grandeur could be greatly improved by a redistribution of the discharge over the Fall, such as to give more depth at the ends of both the Horse Shoe Fall and the American Fall, and so that a much smaller amount of water than at present, would be concentrated in the deep gap at the apex of the Horse Shoe Fall, where it is mostly lost to view and is doing destructive work and churning up a cloud of mist which spreads out so far, and so high that it obscures the view and beauty of the Fall.

The American Fall, meanwhile, has been wearing back at a rate so slow that it can hardly be measured; probably at a rate of not more than one foot per 100 years. The depth over it averages only 1.5 ft. and nowhere exceeds 3.0 ft. Its crest line is about 1,000 ft. long.

The American Fall, which now receives only about one-sixteenth to one-twentieth part of all the water flowing down the Niagara River (although the two countries are understood to be entitled to have equal ownership in the discharge and entitled to share alike in its volume); and it has long been plain that the scenic grandeur could be greatly improved by diverting a slightly larger proportion of the flow to the American Fall, either by means of a channel cut in the bed rock downstream from the deeper water near Port Day, or by means of one or more artificial islands to be built upstream from Goat Island, so as to divert more of the current to the American side, or by both means combined, and restore to it, its former volume.

The beauty of the American Fall is particularly sensitive to change in stage of river, or to depth flowing over it, and looks best with a moderately large flow. Care must be taken not to increase its volume largely beyond that of 50 years ago, lest too large and too powerful an overfall disturb the deep pile of large rocks which protect the base from erosion.

It can be demonstrated beyond reasonable doubt that by means of engineering works comprising a submerged weir such as is recommended by Lieut. Jones, carried along near the crest of the Horse Shoe Fall and concealed from view, resembling the natural ledge in its contour, the present excessive waste of water through this gap at the apex of the Horse Shoe Fall could be prevented; and the whole volume discharging could be so spread out in greater depth at other parts of the Fall as to give even greater scenic grandeur than was presented by natural conditions of fifty years ago. The beauty of the falls could be thus improved notwithstanding a much larger quantity of water is taken for power at some future time than at present. The total length of the over fall of the Horse Shoe Fall is 2½ times as great as that of the American Fall; but the ends need water to cover the cliffs now bare at low stages, or showing relatively small, dribbling streams.

When the real facts, such as are set forth in detail in the report of Lieut. Jones, become broadly known and weighed without prejudice, it can hardly be doubted that popular approval, both in the United States and in Canada will turn toward **making water useful, which is now lost to view, and which now has an injurious effect,** and which has a potential power worth millions of dollars annually, in moving the wheels of industry, in electro-chemistry, and in saving coal.

The Committee on Lake Levels of the Engineering Board of Review, most heartily concurred in the recommendations of Lieutenant Jones, and those of Colonel Warren and the Board of Engineers for Rivers and Harbors, in their proposals to preserve and improve Niagara Falls, by building a submerged dam across the deep gap, and re-distributing the water which now flows therein, lost to beauty and use and causing injury.

In a report to the Chief of Engineers in 1908 it was stated: . . . "the damage already done and that which may be anticipated from further diversions . . . may be largely, if not entirely, remedied by a submerged dam placed in the bed of the river immediately above the Horse Shoe Fall." Ten years later, Lieutenant Jones sought practical means for carrying into effect this suggestion of 1908. His proposed plan and operations is described in great detail on pages 274–8 of the Warren Report.

The present report proposes to apply very much the same remedy, but with the aid of the new design for regulation works located about one mile above the Falls, this remedy of a submerged weir a short distance upstream from the Horse Shoe crest, can be provided at very much smaller cost.

THE NEW DESIGN FOR REPAIR AND PRESERVATION OF NIAGARA FALLS

Location and Type

The present (1924-5) committee of The Engineering Board of Review, appointed to consider the regulation of lake levels, deems the preservation of the scenic beauty of the Falls a matter of very great public interest and importance. It carefully studied the means described in the Warren Report and other possible means and was led to believe that this work of preserving, restoring or increasing the grandeur of the Falls could be carried out at much smaller cost than by the plans described in the Warren Report, by means of a new plan worked out by one of its members which is described and shown by drawings in the following pages, consisting of a "drop-gate weir" combined with a monumental bridge, all located about one mile upstream from Niagara Falls and immediately downstream from the main intakes to the Canadian and the American hydro-electric power plants.

Remedy for Erosion

By means of this new method the crest of the Horse Shoe Fall could be repaired at a cost probably within $200,000 for the submerged weir alone, and without risk or personal danger, instead of the six million dollars estimated by Lieutenant Jones for the 1920 plan of Niagara repairs, which involved many risks and many successive steps in its difficult placing of coffer dams in swift water, close to the brink, and also presumably comprised the wing dam near the head of Goat Island and an extra large and safe margin for contingencies.

Regulating Currents and Unwatering

These works now proposed comprise also a chain of small, irregular, artificial islands with cascades between them, all very much resembling the present small natural islands that lie near Goat Island; these new islands to extend upstream from the head of Goat Island to the middle of the bridge which contains the regulating gates; all so arranged that either the approach to the American Fall or to the Canadian Fall can be unwatered and the bed of the river laid bare temporarily, either during the construction of the bridge or at any future time. The repair of the deep gap at the apex of the Horse Shoe Fall would be quickly done, while the river bed at the brink of the Horse Shoe Fall was thus laid bare. The proposed plan of operations in repairing the crest of the Horse Shoe Fall is described on pages 286 to 288 of the present report.

Comparison of Cost

Designs for this plan for regulation works controlling the elevation and discharge from Lake Erie, with which are combined plans for the repair and preservation and improvement of Niagara Falls have been worked out with much detail, as shown in 10 sheets of drawings attached hereto, and an estimate of cost has been prepared on present day prices, which shows a total cost for regulating weir and all its machinery, and including also the new arched concrete highway bridge, the new ice-channels and the repair of the crest of the Falls, all together would be very little in excess of the cost estimated by the Board on Rivers and Harbors for the regulating works alone at the Head of the Niagara River without any highway bridge; which was about $8,000,000 exclusive of the cost of repairs of the crest of the Falls by the plan proposed by Lieutenant Jones in 1920.

Outstanding Features of Design

Detailed plans for this structure are presented herewith, also an estimate of cost. A perspective outline view of a portion is shown in the cut above, and details are shown in drawings that follow.

The piers are made thin, with sharp ice-breaker nosings on their upstream ends, and the arches of the bridge serve to stiffen and give transverse support to the thin piers, and also to give access to the gate mechanism.

These weir-gates, sixty in number, are to consist each of an inclined steel gate, in construction somewhat similar to a lock gate, but adjustable about a horizontal axis at the bottom edge, which is supported in a massive concrete sill resting upon the nearly level limestone bedrock of the Niagara River.

The gates are made extremely simple in design and adapted to avoid injury from ice. The semi-cylindrical top is for a "bumper" to withstand impact of ice or logs and carries no structural load. The clear width of gate openings was limited by economy of weir gate design, but is surely ample for prevention of clogging by ice.

They are so designed that any one of them can be readily hoisted out for repairs, and the piers include stop log grooves for permitting quick unwatering of each sluiceway.

Each of these gates is suspended from its top corners by strong chains which can be raised or lowered by winches operated by electric power, with mechanism so designed that one or all of the gates can be laid flat at the bottom of the channel, permitting an unobstructed flow for running out ice or for flood discharge, or can be raised or lowered to any desired degree. The winch shown in the drawings is designed to cover the entire range of height in about half an hour but obviously could be designed to work faster.

By the operation of these adjustable weirs the level of the Chippawa Pool can be raised to any desired extent from zero up to ten or eleven feet; or in connection with an extension from Goat Island upstream the flow of water in either half of the channel, on either side of the International boundary, can be entirely shut off while full ordinary discharge of the Niagara River (less the power draft and less storage held back in Lake Erie, by closing the gates), is given sufficient passageway through the other half.

It **now seems certain that means will be found by which the present development of hydro-electric power both on the American and on the Canadian sides can be more than doubled without detracting from the Scenic Grandeur of Niagara Falls:** and that this cheap power in connection with the remarkable opportunity for a long chain of industrial sites along this river shore, located virtually at the foot of Great Lakes navigation, presents opportunities requiring most serious consideration while planning control works at the foot of Lake Erie.

It was in order to give more definiteness to this suggestion, and in order that direct comparisons may be made with designs and costs of previous projects, that the detailed plans of the proposed structure have been prepared, together with an approximate estimate of cost; and it is found that the total cost, exclusive of embankment and Lock at Tonawanda but including both the proposed regulating works and a new concrete, arched bridge of ample width, will probably not exceed $8,000,000 or no more than the cost of regulating works such as proposed at the outlet of Lake Erie near Buffalo without any bridge, without extension of harbor, without the advantages for increasing head in the power canals, and without the convenient opportunity for unwatering either side of Niagara Falls for the construction of protecting works.

There appears no possibility whatever that the cost of the whole project need be so large that excess of cost would be a determining factor.

THE NEW PLAN FOR REGULATION OF LAKE ERIE

The plan now proposed differs from that of the Board of Engineers on the Deep Waterways of 1900, and from that of the Board on Rivers and Harbors of 1922, chiefly in a change of location of the regulating works from the outlet of Lake Erie to a point about 20 miles downstream and only about one mile back from the crest of Niagara Falls. Also it differs in the type of gate proposed and in the inclusion of an International Bridge across the Niagara River over the sluiceways.

The change in location permits realizing the following improvements over these two previous designs for gates at the head of the Niagara River:

(1) The extension of terminal harbor facilities from Buffalo 20 miles downstream, with 30 feet of depth available for larger boats throughout this distance either via the present Black Rock Canal, or via the present main channel after a moderate amount of deepening and widening at the throat of the gorge.

This extension of harbor facilities for the terminus of the American Great Lakes traffic, falls excellently into line with plans now in progress for developing a great railroad freight yard on Grand Island, and also permits great future industrial development on both the American and Canadian shores, of the upper Niagara River and upon Grand Island in connection with increased power development possible at Niagara Falls.

(2) This moving the gates downstream permits them to aid in creating slack water through the present rapids in the gorge-channel at the outlet of lake Erie.

(3) The removal of the gates to a point just downstream from the two chief water power intakes will greatly aid in providing additional power at Niagara, particularly upon the Canadian side, where the increased head of from five to ten feet will give that additional depth throughout the long and expensive canal from Chippawa to Queenstown, thereby increasing its water carrying capacity perhaps 50%.

(4) Placing the regulating gates in close proximity to Niagara Falls permits quicker adjustment of quantity discharged over the falls for meeting emergencies of wind or weather, or for special occasions.

(5) By placing the gates close to the Falls at the head of a divided channel, the quantities flowing over the American Fall and the Canadian Fall can be quickly adjusted, and the American Fall can be given sufficient quantity to cover its crest now laid bare in large part at times of obstruction by ice lodged upon the shallow ledge near head of Goat Island.

(6) By placing the regulating gates near the power intake at the entrance to channels to be cut in the bed rock shown in sheet No. 1 of attached drawings, page 276 A, they can be operated so as to give great assistance in running out ice and preventing interruptions to the power service.

(7) The removal of the regulating works from a position directly at the outlet of Lake Erie, to one 20 miles downstream, removes all grounds for fear that the lodgement of ice against the works would delay the opening of Buffalo harbor in the spring.

(8) By placing the regulating works near the Falls at the head of a divided channel it becomes possible to unwater either the American Fall or the Canadian Fall temporarily for the purpose of levelling up the crest eroded, so as to spread the discharge over the whole width of the Fall.

By this means it will be practicable to repair and level up the crest of the Horse Shoe Fall and fill the gap near the deep notch, all for the expenditure of somewhere between $100,000 and $200,000 instead of a large part of the $6,000,000 estimated by Lieutenant Jones in the Warren Report, as necessary by the method of cofferdams and tunnels therein proposed, and with much less risk to structures and less personal danger. Also this work of repairs can be completed in much less time.

With all of the gains above noted, the regulation works as now proposed lose nothing in opportunities, or facilities, for controlling the level of Lake Erie, in comparison with those proposed at head of river in 1900 and 1921, and probably will cost little if any more than the estimates for gates and sluiceways at the outlet of the lake, notwithstanding that a new highway bridge of generous width is incorporated in the design now submitted.

As compared with the methods and works proposed by the International Waterways Commission in 1910 and 1913, comprising a submerged weir across the Chippawa Pool upstream from the power intakes, or the method proposed in the Warren Report in 1921 by Engineer Richmond and approved by Colonel Warren, the method with regulating gates plainly is vastly superior to an immovable weir, in giving **regulation** instead of **compensation** for the six inches of lowering of Lake Erie that has been caused by the several diversions. The new designs accomplish all that the systems of submerged weirs could accomplish, and, in addition thereto give storage control of Lake Erie and an ordinary increase of depth amounting to about 2 feet throughout its navigation channels.

Those systems heretofore proposed which comprised only submerged compensation weirs, gave no storage whatever, no increased elevation for Lake Erie and no increase in the harbor facilities downstream from Buffalo.

The proposed regulation works are designed to hold the Chippewa Pool at any desired increased elevation from about 1 foot up to 11 feet above its present natural height, and they can be dropped within a few minutes to any desired amount to accommodate a seiche, or relieve effects of change of lake level caused by strong wind or for running out ice, or to give an exceptionally deep sheet of water over either the Canadian or the American Falls for temporary spectacular purposes.

The gates are given extra height for the purpose of holding back water in Lake Erie while unwatering either channel above the Falls.

Any or all of these gates can be quickly dropped so as to lie flat on the river bed and then discharge substantially as freely as in the state of nature.

It is proposed that the operation of these regulation works be under control of a small International Executive Committee.

CONTROL OF LAKE ERIE'S ELEVATION BY A DAM 20 MILES DOWNSTREAM

Since there is under all ordinary conditions a fall of about 10 feet in the Niagara River in the 20 miles length between Lake Erie and the proposed dam site, and since there is a relatively narrow gorge at the head of the Niagara River, within the swift waters of which about four feet of the total drop occurs in a distance of about 1½ miles, those unfamiliar with the hydraulics of these great rivers may very properly ask if dam and sluiceway gates located so far down from Lake Erie will surely and promptly effect the desired control.

Fortunately, excellent data were at hand for making the necessary hydraulic computations, these being given in the charts of the U. S. Lake Survey and in the careful profiles of river height obtained by special surveys for the International Waterways Commission of 1910 to 1913. It was the time taken between 1910 and 1913 for running new lines of precise levels and the setting and observation of many new gages for accurately determining this water profile between Lake Erie and the foot of the Chippawa Pool, which delayed the final report of the International Commission three years, from 1910 to 1913.

The computations based on this data and described on pages 294 to 309 of this report, prove

(1) That at ordinary river stages with the average flow of 209,000 cu. ft. sec. **by raising the surface of the Chippawa Pool eight feet (to elevation 570), Lake Erie can be raised to the utmost height proposed,** or to elevation 574.5.

(2) That, with the proposed minimum regulated discharge of 180,000 cu. ft. sec. for which the natural elevation of Chippawa Pool is 561.3 and the natural elevation of Lake Erie 571.3, by raising the gates 10.1 ft., or so as to raise Chippawa Pool, to 571.4, Lake Erie will be raised to the proposed maximum of 574.5, and

(3) That the river banks are high enough so that by means of a low dike along the American shore to Tonawanda and a new lock at the entrance of the new Erie Canal, all this can be safely accomplished within reasonable limits of cost.

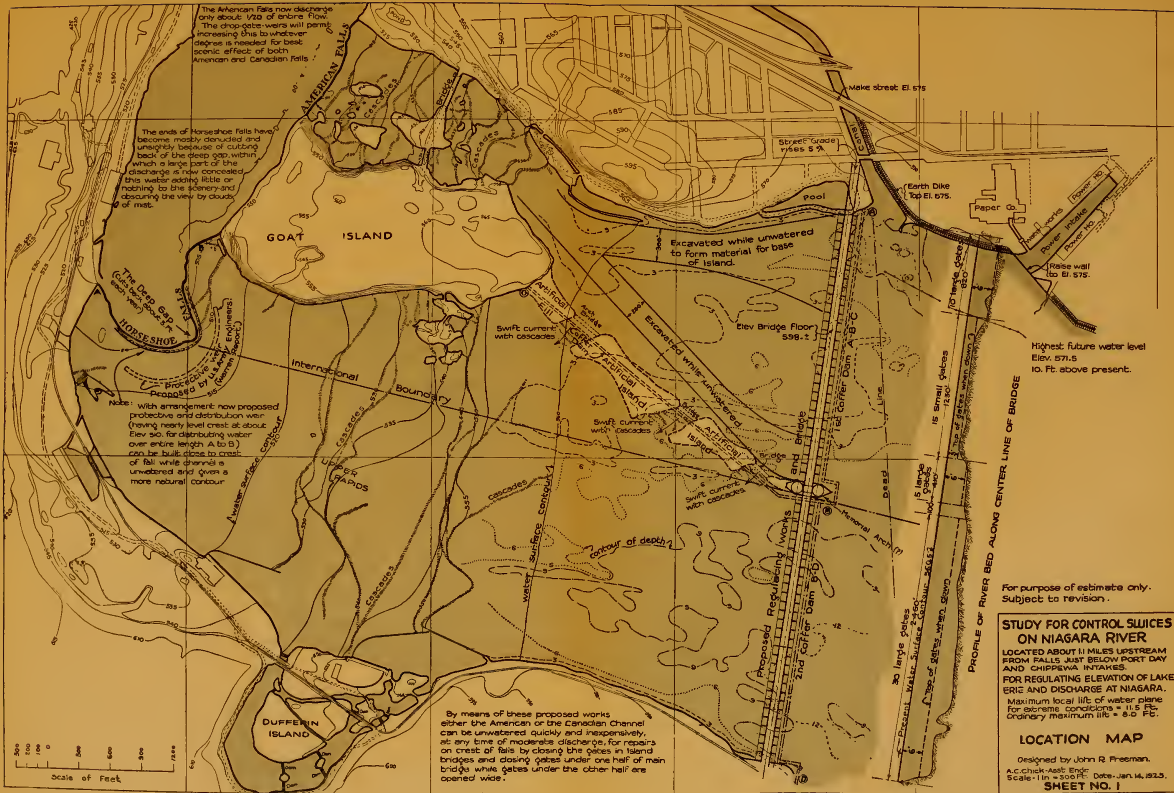
The river banks between the regulation works and Tonawanda are so near the proposed maximum height in the Chippawa Pool that a low dike will be needed, also a new lock at the entrance to the Erie Canal. A reconnaissance along the shore by the writer of this report has shown these involve no special difficulties.

No estimate for the cost of this dike is included because of the probability that other scenic or practical features would be joined with it, such as a shore line boulevard, or wharves for future commerce.

LOCATION MAPS AND STRUCTURAL DRAWINGS

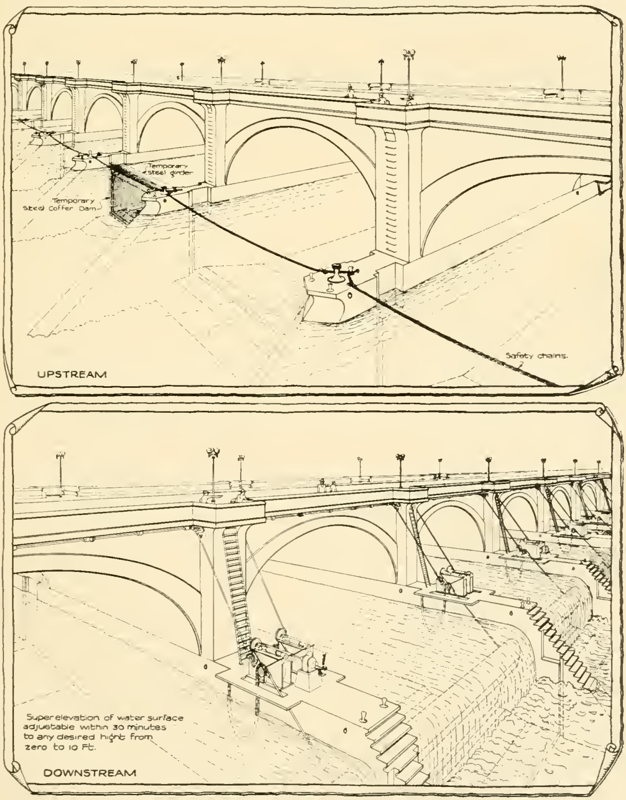
Reproduction, on a reduced scale, of the more important drawings necessary for understanding the structural features, are presented in the following pages.

The first is a map showing the proposed location for the regulating works, about one mile above the Falls, just downstream from the intakes of the principal American and Canadian waterpower developments. On each the American and the Canadian sides all of the main power plants are now consolidated under a single management. The older plants on the Canadian side located on the banks of the river near the Falls, use the water with only about half the economy of the new Queenston plant and are mostly idle, as reserves or in "stand-by" service.

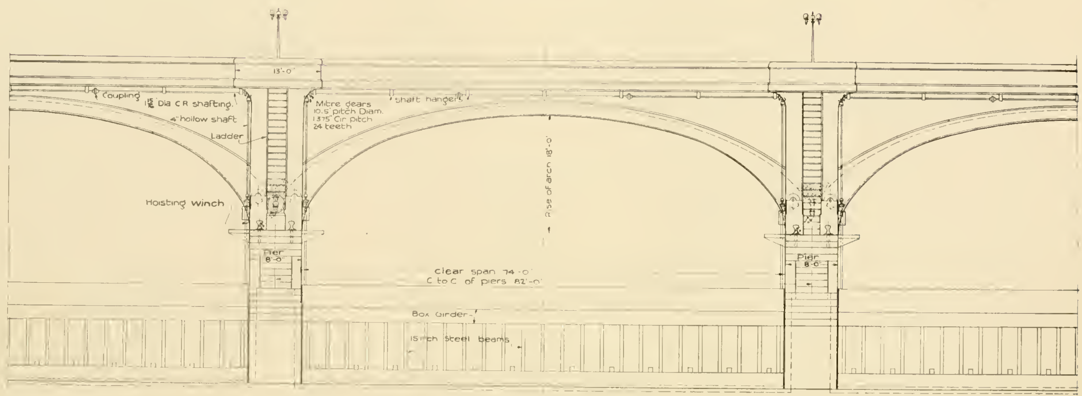

The American Falls now discharge only about 1/20 of entire flow. The drop-gate-weirs will permit increasing this to whatever degree is needed for best scenic effect of both American and Canadian Falls
AMERICAN FALLS
Cascades
Bridge
Make street El. 575
The ends of Horseshoe Falls have become mostly denuded and unsightly because of cutting back of the deep gap, within which a large part of the discharge is now concealed, this water adding little or nothing to the scenery and obscuring the view by clouds of mist.
Street Grade rises 5 ft.
Canal
Earth Dike Top El. 675.
Paper Co.
Pool
GOAT ISLAND
Excavated while unwatered to form material for base of Island.
Power Ho.
Power Intake
Raise wall to El. 575.
The Deep Gap (cuts back about 5 ft. each year)
HORSESHOE FALLS
Protective weir Proposed by U.S. Army Engineers (Warren Report)
Artificial Fill
Arch Bridge
Coffer Dam
Artificial Island
Swift current with cascades
Excavated while unwatered
Elev Bridge floor 598.±
1st Coffer Dam A-B-C
Dead Line
15 Small gates 1230'
10 large gates 820'
Top of gates when down
Highest future water level Elev. 571.5 10. Ft. above present.
International Boundary
Note: With arrangement now proposed protective and distribution weir (having nearly level crest at about Elev 510. for distributing water over entire length A to B) can be built close to crest of fall while channel is unwatered and given a more natural contour
water surface contour
UPPER RAPIDS
Cascades
Swift current with cascades
Bridge
and Bridge
Memorial Arch (?)
5 large gates 410'
contour of depth
Proposed Regulating Works
2nd Coffer Dam B-D
30 large gates 2460'
Present Water Surface Contour 560±2
Top of gates when down
PROFILE OF RIVER BED ALONG CENTER LINE OF BRIDGE
For purpose of estimate only. Subject to revision.
STUDY FOR CONTROL SLUICES ON NIAGARA RIVER
LOCATED ABOUT 1.1 MILES UPSTREAM FROM FALLS JUST BELOW PORT DAY AND CHIPPEWA INTAKES.
FOR REGULATING ELEVATION OF LAKE ERIE AND DISCHARGE AT NIAGARA.
Maximum local lift of water plane For extreme conditions = 11.5 Ft. Ordinary maximum lift = 8.0 Ft.
LOCATION MAP
Designed by John R. Freeman.
A.C. Chick - Asst Engr.
Scale - 1 In = 500 Ft. Date - Jan. 14, 1925.
SHEET NO. 1
DUFFERIN ISLAND
By means of these proposed works either the American or the Canadian Channel can be unwatered quickly and inexpensively, at any time of moderate discharge, for repairs on crest of falls by closing the gates in Island bridges and closing gates under one half of main bridge while gates under the other half are opened wide.
Scale of Feet

DAM, SLUICES, GATES AND BRIDGE ABOVE NIAGARA FALLS

These works, now proposed, are to consist of a series of 60 large drop-gate weirs each of 74 feet clear span, extending entirely across the river which here is nearly one mile in width. These weirs would be supported between piers of a new monumental arched concrete bridge to be built between the city of Niagara Falls in the United States and the Village of Chippawa or Niagara Falls in Canada; for which bridge there is said to be great need during the summer tourist season and a strong popular demand.



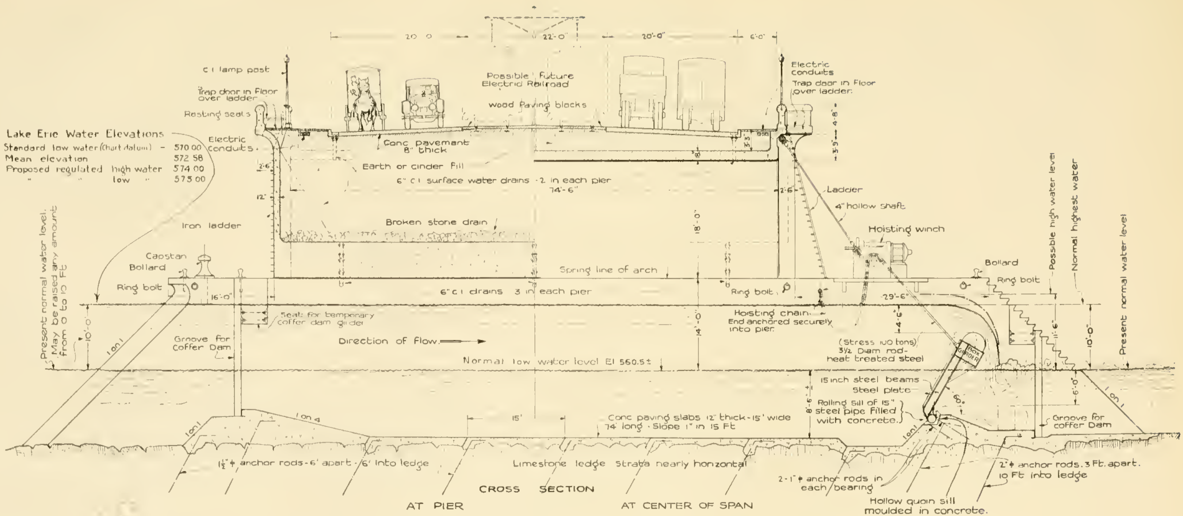
VIEWS OF PROPOSED REGULATING WORKS



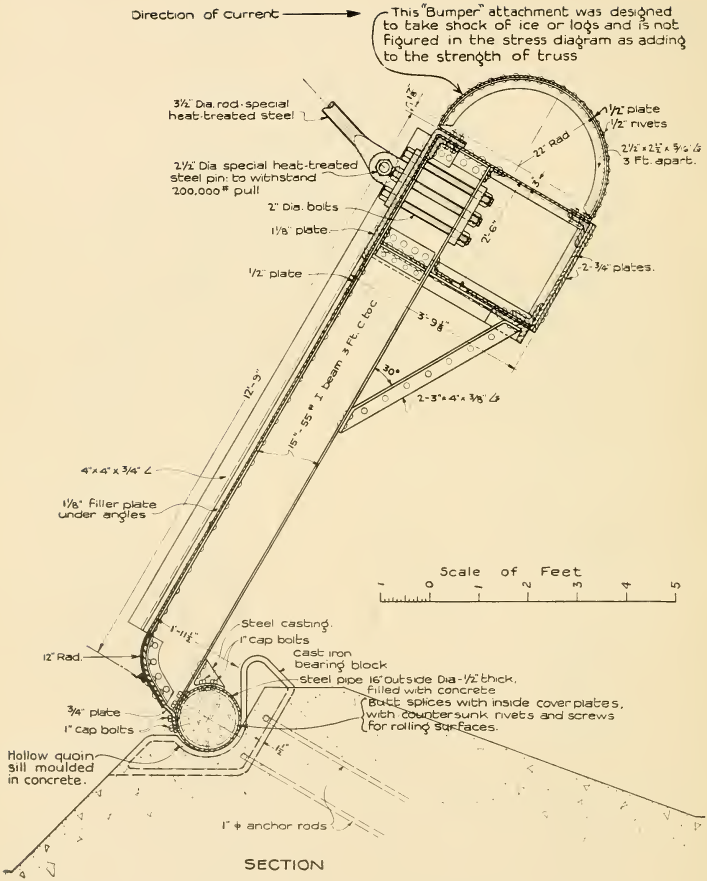
ELEVATION LOOKING UPSTREAM

PROPOSED REGULATING WORKS IN NIAGARA RIVER

(One important purpose of the bridge is to support and stiffen the piers between regulating gates, which are made thin to lessen resistance to floating ice.)



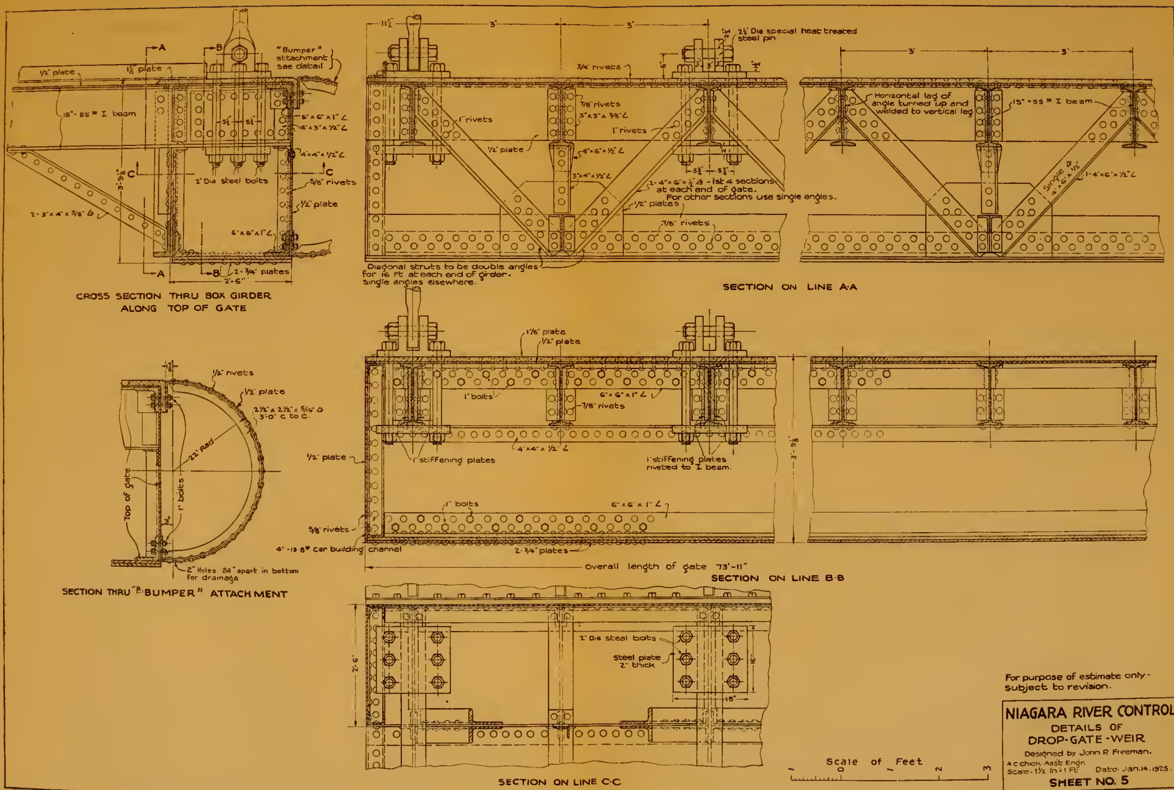
CROSS SECTION OF REGULATING WORKS AND BRIDGE PROPOSED ACROSS THE NIAGARA RIVER ABOUT 1 MILE ABOVE FALLS

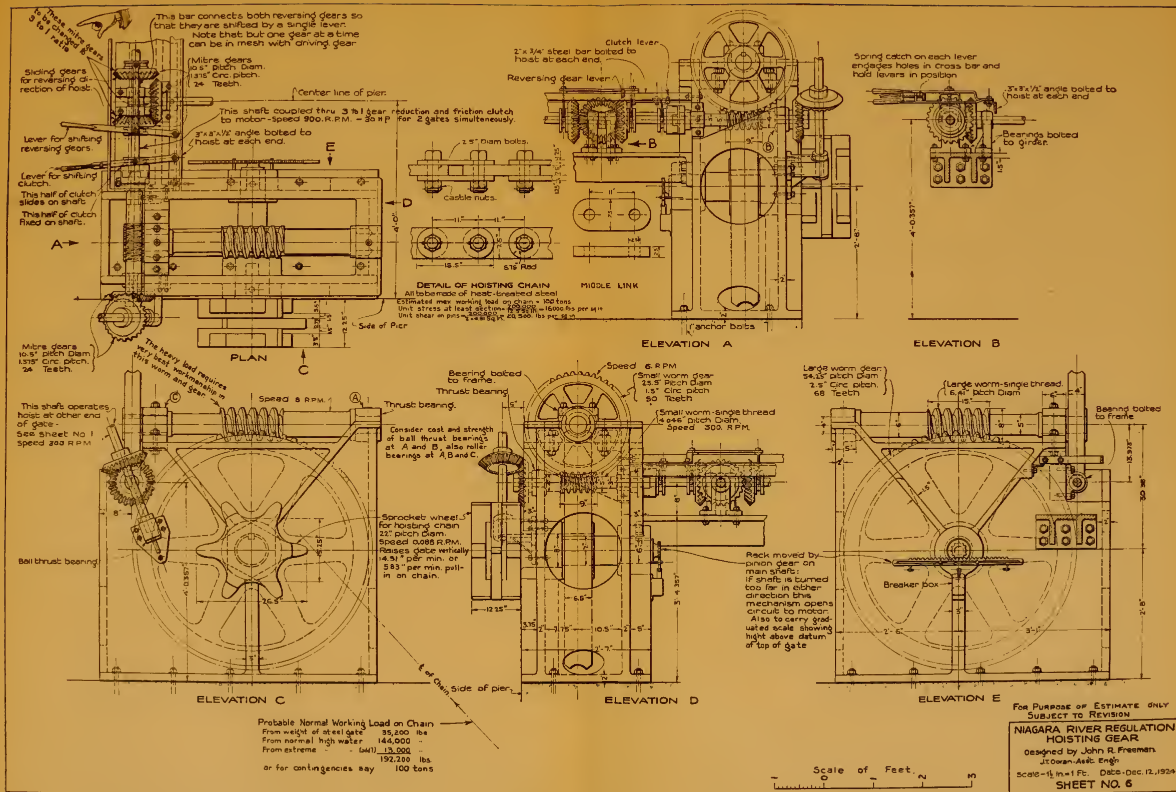


VERTICAL CROSS-SECTION OF REGULATING GATE

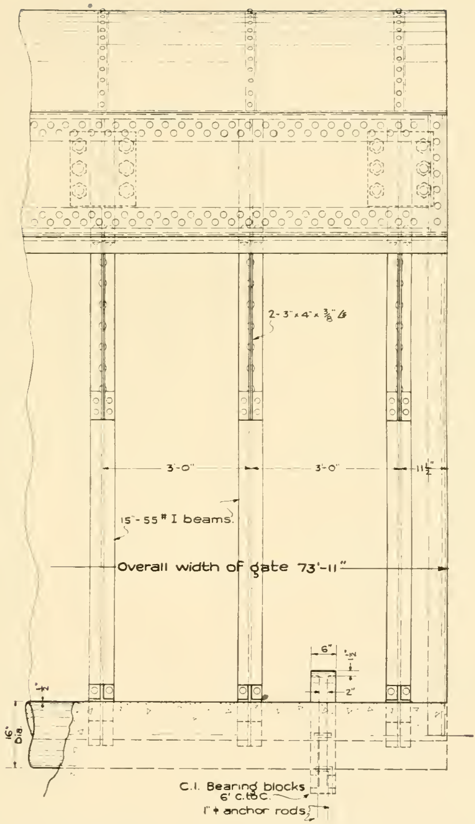
Built of steel plates and structural shapes

Shown at normal full height


CROSS SECTION THRU BOX GIRDER ALONG TOP OF GATE
"Bumper" attachment see detail
1/2" plate
1 1/8" plate
15"-55# I beam
6"x6"x1" ∠
4"x3"x1/2" ∠
4"x4"x1/2" ∠
2" Dia steel bolts
5/8" rivets
1/2" plate
2-3"x4"x3/8" ∠s
6"x6"x1" ∠
2-3/4" plates
2'-6"
SECTION ON LINE A-A
2 1/2" Dia special heat treated steel pin
3/4" rivets
1" rivets
7/8" rivets
3"x3"x3/8" ∠
1/2" plate
4"x6"x1/2" ∠
3"x4"x1/2" ∠
2-4"x6"x1/2" ∠s - 1st 4 sections at each end of gate. For other sections use single angles.
1/2" plates
Diagonal struts to be double angles for 16 ft at each end of girder. Single angles elsewhere.
Horizontal leg of angle turned up and welded to vertical leg
15"-55# I beam
1-4"x6"x1/2" ∠
SECTION THRU "BUMPER" ATTACHMENT
1/2" rivets
1/2" plate
2 1/2"x2 1/2"x5/16" ∠s 3'-0" c to c.
22" Rad
Top of gate
1" bolts
2" Holes 24" apart in bottom for drainage
SECTION ON LINE B-B
1 1/8" plate
1/2" plate
1" bolts
6"x6"x1" ∠
7/8" rivets
4"x4"x1/2" ∠
1" stiffening plates
1" stiffening plates riveted to I beam.
1/2" plate
1" bolts
6"x6"x1" ∠
5/8" rivets
4"-13.8# car building channel
2-3/4" plates
Overall length of gate 73'-11"
3'-9 1/8"
SECTION ON LINE C-C
2" Dia steel bolts
Steel plate 2" thick
16"
18"
2'-6"
For purpose of estimate only - subject to revision.
Scale of Feet
NIAGARA RIVER CONTROL
DETAILS OF
DROP-GATE-WEIR
Designed by John R Freeman.
Scale - 1 1/2 In = 1 Ft
Date - Jan. 14, 1925.
SHEET NO. 5

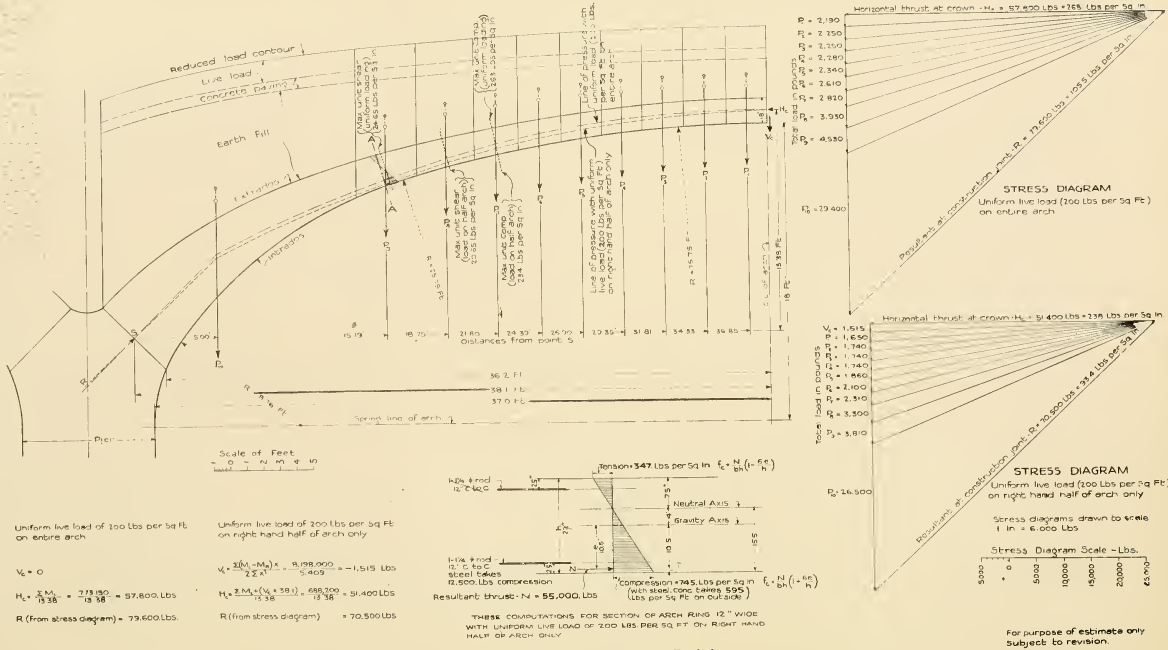


These mitre gears to be changed to 3 to 1 ratio
This bar connects both reversing gears so that they are shifted by a single lever. Note that but one gear at a time can be in mesh with driving gear
Mitre gears 10.5" pitch Diam. 1.375" Circ. pitch. 24 Teeth.
Sliding gears for reversing direction of hoist.
Center line of pier.
This shaft coupled thru 3 to 1 gear reduction and friction clutch to motor-Speed 900. R.P.M. - 30 H P for 2 gates simultaneously.
3"x3"x1/2" angle bolted to hoist at each end.
Lever for shifting reversing gears.
Lever for shifting clutch.
This half of clutch slides on shaft
This half of clutch fixed on shaft.
2.5" Diam bolts.
Castle nuts.
Side of Pier
PLAN
DETAIL OF HOISTING CHAIN
All to be made of heat-treated steel
MIDDLE LINK
Clutch lever
2" x 3/4" steel bar bolted to hoist at each end.
Reversing gear lever
1" anchor bolts
ELEVATION A
Spring catch on each lever engages holes in cross bar and hold levers in position
3"x3"x1/2" angle bolted to hoist at each end
Bearings bolted to girder.
ELEVATION B
Mitre gears 10.5" pitch Diam 1.375" Circ. pitch. 24 Teeth.
The heavy load requires very best workmanship in this worm and gear.
This shaft operates hoist at other end of gate - See Sheet No 1 Speed 300 R.P.M.
Speed 6 R.P.M.
Thrust bearing.
Consider cost and strength of ball thrust bearings at A and B, also roller bearings at A, B and C.
Sprocket wheel for hoisting chain 22" pitch Diam. Speed 0.086 R.P.M. Raises gate vertically 14.91" per min. or 5.83" per min. pull-in on chain.
Ball thrust bearing.
ELEVATION C
Bearing bolted to frame.
Thrust bearing
Speed 6 R.P.M.
Small worm gear 25.9" Pitch Diam 1.5" Circ pitch 50 Teeth
Small worm-single thread 4.046" pitch Diam. Speed 300. R.P.M.
Side of pier.
ELEVATION D
Large worm gear. 54.15" pitch Diam 2.5" Circ. pitch. 68 Teeth
Large worm-single thread. 6.41" Pitch Diam
Bearing bolted to frame
Rack moved by pinion gear on main shaft: If shaft is turned too far in either direction this mechanism opens circuit to motor. Also to carry graduated scale showing hight above datum of top of gate
Breaker box
ELEVATION E
Probable Normal Working Load on Chain
From weight of steel gate 35,200 lbs
From normal high water 144,000
From extreme 13,000
192,200 lbs.
or for contingencies say 100 tons
Scale of Feet.
For Purpose of Estimate Only Subject to Revision
NIAGARA RIVER REGULATION HOISTING GEAR
Designed by John R. Freeman.
J.T. Ooran-Asst. Engr.
Scale-1½ in.=1 Ft. Date-Dec. 12, 1924
SHEET NO. 6

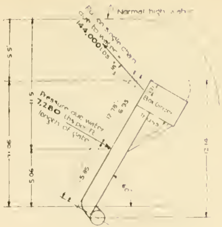


PART ELEVATION OF DOWNSTREAM SIDE

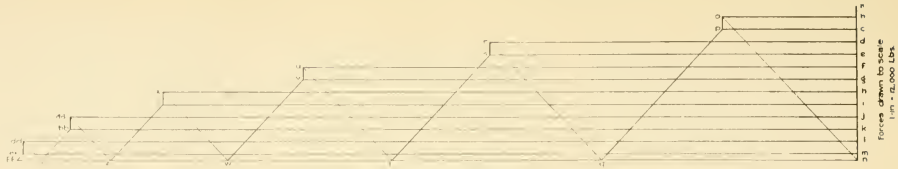
REGULATING GATE



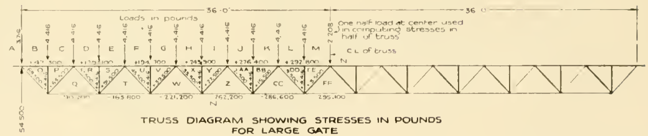
ANALYSIS OF STRESSES IN ARCH RING



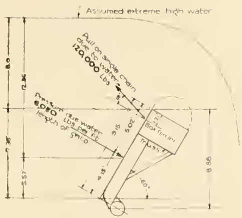
FORCES ACTING ON LARGE GATE
DUE TO WATER



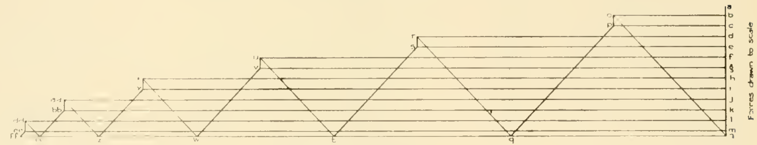
STRESS DIAGRAM
TRUSS FOR LARGE GATE



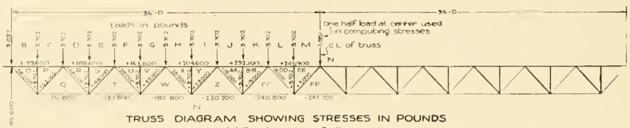
TRUSS DIAGRAM SHOWING STRESSES IN POUNDS
FOR LARGE GATE



FORCES ACTING ON SMALL GATE
DUE TO WATER



STRESS DIAGRAM
TRUSS FOR SMALL GATE



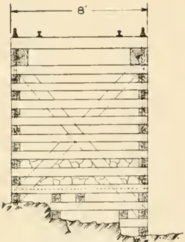
TRUSS DIAGRAM SHOWING STRESSES IN POUNDS
FOR SMALL GATE

Tension members shown thus −
Compression " " " +

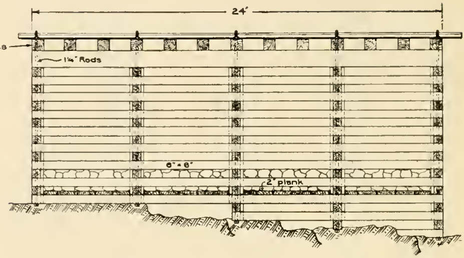
For purpose of estimate only.
Subject to revision

POSSIBLE STRESSES IN GATES

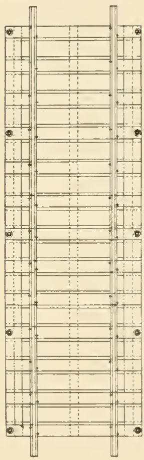
DETAILS OF COFFERDAM



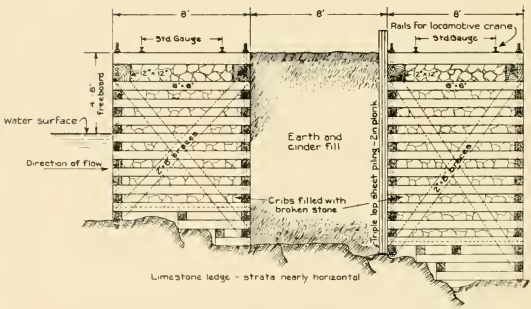
END VIEW
TYPICAL SECTION



SIDE VIEW ~ TYPICAL SECTION



PLAN



SECTION OF COFFER DAM ~ ASSEMBLED

PLACING OF COFFERDAMS

First it is to be noted from the Shenehon survey of 1910 that velocity of current is small all the way across the river at the side of the bridge, and that the depths to bedrock also are small.

Floods or extreme fluctuations in height of surface of Niagara near the Falls are not known. Thus conditions for building cofferdams rapidly and cheaply are exceptionally favorable.

In order to obtain a firm bearing and level courses of crib work, soundings will be made just prior to placing each 24-foot section of crib, by means of a framework about 26 feet long by 10 feet in width, swung from a locomotive crane and held in contact with the end of the preceding crib. The measurements will be taken by iron rods sliding in pipes fixed firmly into this framework so that depth and contour of the ledge or other bottoms at each contour of the crib and the numerous intermediate points will be precisely known, and blocking fitted to the bottom of the level courses of the next crib before swinging it into place.

These cofferdams are to be comprised primarily either 12 feet or 24 feet in length, according to depth and strength of the current, built on shore and transported partially ballasted with stone, and swung into position by two locomotive cranes assisting each other and running on the railroad tracks shown on the tops of each of the parallel cribs.

Ordinarily, the down-stream crib extension will be placed by the down-stream crane first, and held in position by the up-stream crane, while the down-stream crane quickly completes filling it and ballasting it with loose, rough blocks of stone.

Next the up-stream crane will be swung into place, while it also is filled with loose stone.

Shortly behind the extension of the crib tongued and grooved sheet piling will be driven to firm contact with the river bed, as shown, and the space between the two cribs then filled with carefully graded gravel and fine earth of a gravelly character.

After completion of each half of the bridge, the cofferdam will be completely torn out, either by cranes and orange peel buckets working from an exceptionally large and stable scow, which is to be built as part of the permanent equipment, or by other convenient means.

It will be noted that it is propcsed to first build and complete the entire American section to the monumental central pier, and that a cofferdam will be built only upon the up-stream side; while a wing dam of similar crib-work is build frcm the central pier down-stream to the head of Goat Island. This central wing cofferdam serves fcr both the American and Canadian section of bridge and sluiceways. Also it serves in the unwatering first of the American channel, while excavating ledge to give increased depth over the American Fall. Material thus excavated in the dry to be transported on industrial railways and dumped to form artificial islands.

ESTIMATE OF COST OF NIAGARA RIVER REGULATION WORKS

Item	Quantity	Unit Cost	Cost per span	Total 60 spans
	(Total)			
1. Coffer-dams: See details on Sheet No. 9. 1st coffer A. B. C. from American shore to midstream thence to Goat Island	(lin. ft.) 6,800	$60		$ 408,000
2nd coffer B. D. from midstream to Canadian shore	(lin. ft.) 2,500	60		150,000
Additional coffer-dam across end of first Canadian section say 1,500 lineal feet of smaller section than on upstream side		50		75,000
2. Preparing ledge foundation for bridge	(cu. vd.) 95,000	3		285,000
	(per span)			
3. Concrete in Bridge & Piers: Foundation piers for memorial arch 100′ wide x 350′ long. Including forms and centers	(cu. yd)			
(concrete)	10,000	20		200,000
(Rock Fill)	36,000	3		110,000
Superstructure, including road (sub surfaces)	(cu. yd.) 900	25	$22,500	1,350,000
Piers (average)	(cu. yd.) 1,090	20	21,800	1,308,000
Facing for river bed between piers	(cu. yd.) 850	20	17,000	1,020,000
Reinforcement	(tons) 50	100	5,000	300,000
4. Wood Block paving for roadway	(sq. yd.) 200	3	600	36,000
5. Earth fill for spandrels of arches	(cu. yd.) 1,470	3	4,410	264,600
6. Rock fill for drains at piers	(cu. yds.) 30	3	90	5,400
7. Drain pipe—6″ cast iron (lbs.)	1,080	3c.	35	2,100
8. Steel drop-gates (average) (45 large & 15 small gates) with "flashboard" attachments	(tons) 54.0	$200	10,800	648,000
				$6,162,100
	(per span)			
9. Bearing blocks for gate (cast iron) (pounds)	6,000	10c.	600	36,000
10. Hoisting gear with motor	1	$7,000	7,000	420,000
11. Hoisting chains (pounds)	8,200	20c.	1,640	98,400
12. Shafting—including bearings etc., from one pier to another end of gate			2,550	153,000
13. Bearing Plates for needle bars (pounds)	13,600	6c.	816	49,000
14. Lamp posts	2	50	100	6,000
15. Electric conduit-tile-ft.	500	5c.	250	15,000
16. Trap doors	2	10	20	1,200
17. Iron ladders—upstream side	1	50	50	3 000
18. Iron ladders—downstream side	1	100	100	6,000
19. Ring bolts	7	5	35	2,100
20. Bollards	5	75	375	22,500
21. Geared capstan	1	300	300	18,000
22. Claw hooks	2	25	50	3,000
23. Guard chain 100 ft. long (1½″ diameter)	(lbs.) 2,500	10	250	15,000
				$7,010,300
Engineering 6%				$ 420,600
				7,430,900
Contingencies 10%				743,100
			Total	$8,174,000

Note: — Contingencies here are uncommonly small because of complete surveys, uniform and fairly level ledge river bed, absence of floods and shallow depths of water, the proximity to great machine shops and facilities for transportation, and low cost of concrete aggregate, all favor small emergency expense.

While under construction, the site of that half of bridge and gates which lies on the American side of the International Boundary is to first be enclosed by a coffer-dam, which after extending half way across the river to just beyond the international boundary, there turns directly down-stream at nearly a right angle, toward the upper extremity of Goat Island, all as shown on Sheet No. 1 of drawings attached.

The Canadian channel is of such ample capacity that the American Channel will thereby become unwatered, presenting opportunity for rapid and economical excavation of two broad and rather shallow channels in the level strata of the limestone bed rock, substantially as shown on Sheet No. 1 of attached drawings. One of these channels, 200 ft. wide, located near the international boundary would serve to provide more water to the American Fall or serve for the rapid discharge of ice from opened gates. The other channel near the American shore, 300 ft. in width, would presumably be excavated by the power companies for facilitating the running out of ice from their intakes. These two channels would join near the head of Goat Island in a single channel about 500 ft. wide leading down past the second cascade.

The upstream easterly corner of Goat Island may need to be cut away very slightly or the throat of the adjacent American Channel deepened, in order to facilitate at a later stage the discharge over the American Fall of all the water in the Niagara River left flowing after temporarily opening to their fullest capacity all of the unused water power turbines on both sides of the river during the brief period while the crest of the Horse Shoe Fall is under repair, **meanwhile holding back in temporary storage in Lake Erie** the surplus beyond what can be carried on one side of Goat Island.

The material from the channel near the international boundary and perhaps also that from the other new channel excavations, would be deposited along the coffer-dam to form the base of two or three new artificial islands (as shown on attached plans) each of irregular outline similar to the near-by natural islands, and with the open channels between them carefully designed to give pitcuresque cascade effects, like those between the present small islands upstream from the American Fall.

On top of this broken rock foundation for these islands would be placed sand and loam of sufficient depth for growing shrubbery and large trees, all placed in a natural manner, or similar to those on the adjacent natural islands. A road and foot paths would extend over these islands, with smaller arched bridges over the channels similar to the bridges between present islands, but with hidden gates or sills etc., beneath these bridges for quickly placing coffer-dams to be used in unwatering either Fall, for examination, readjustment or repair of crest at any future time.

At present the channel to the American Fall carries only about one sixteenth to one twentieth part of the entire natural discharge of Niagara River. These two Main Channels leading from the adjustable drop-weir gates would permit increasing the discharge over the American Fall to any degree desired for producing the best scenic effects, and this discharge could be readily readjusted from time to time, or from hour to hour, on special occasions.

REPAIRING DEEP GAP IN CREST OF HORSE SHOE FALL

After completing within its coffer-dams the American half of the bridge and weirs, the Canadian channel could be closed off half at a time, similarly by a coffer-dam.

During the construction of the second half, or later, the Canadian channel could be unwatered, thus giving opportunity for constructing protective works along the crest in the deep notch near the apex of the Horse Shoe Fall, substantially as proposed on page 47 and pages 253 to 281 of the "Warren Report", but in closer proximity to the crest of the Fall, with more effective shapes, and with far less expense and danger.

By means of building this protective weir for levelling up the crest, **the deep, strong current now tearing down through the deep notch at the apex of the Horse Shoe Fall would have its errosive power mostly taken away** and the water now passing through the deep notch would be spread out in a more nearly uniform sheet over the now denuded ends of the Canadian Fall, and the large high cloud of mist and fog from the discharge through the deep notch, which now obscures and detracts from the beauty of the Horse Shoe Fall, would be lessened, all very much as described by the Board of Engineers on Rivers and Harbors and by Lieut. Jones in Appendix C of the "Warren Report," but at far less cost and danger.

Of course this new concrete weir on the apex of the Horse Shoe Fall should be built in a rough and irregular form resembling the native ledge, notwithstanding it would be concealed beneath the overflowing water. The facility with which either channel can be unwatered by means of regulation works built near the Falls permits constructing this new distributing weir, upstream from the Horse Shoe crest, at successive stages and trying out the effect, or making various adjustments or re-distributions of the flow from time to time.

One important reason for placing this new irregular weir as close as practicable to the brink, say within 40 or 50 feet, is in order that the water after passing over it in a nearly uniform depth will reach the main overfall in a solid sheet, without becoming separated into broken streams. The aim should be to obtain all of the way around the brink, the effect now found in the most beautiful portions of the falls.

It is worthy of note, as demonstrating the protection and preservation to be expected from the proposed treatment of the crest, that while the Horse Shoe Fall has, during the past century, been cut back at the rate of from four to six feet a year, and its original beauty meanwhile largely impaired by this errosive power of this deep current, **the American Fall with its smaller and more uniform depth has shown no noteworthy recession.**

The American Fall also would be restored to its former beauty by covering its denuded ends with the slightly larger flow that can be put through the new channels mentioned above, by opening one or more gates, and this volume of water can always be kept at its best, instead of as now being sometimes badly depleted by low water caused by an up-lake wind or an ice-gorge.

In brief, this design for these works permits of quickly adjusting the discharge in both the American and the Canadian Channel to any desired reasonable quantity or proposition; permits counteracting the effect of seiches or ice jams upon the flow over the Falls; **permits storing part of the flow late at night for release by day,** or when more people can enjoy the spectacle; and by opening the gates all wide open, the conditions of natural flow can at any time be restored.

The close proximity of the regulating works to the crest of the Falls presents a great advantage over a location 20 miles away, for all of these conditions.

Moreover, for any grand occasion the flow for a few hours could be largely increased to the very largest amount ever observed under natural conditions in years prior to diversions for power.

DISCHARGE CAPACITY OF UPPER NIAGARA RIVER WHILE REGULATING WORKS ARE UNDER CONSTRUCTION

The width of the river here in the Chippawa pool is about one mile, at the proposed site of the gates, so that the back-water caused by the piers of the bridge and by the drop-gates when completely lowered, will be hardly noteworthy in times of highest natural discharge. The sills of all the gates are designed to lie as close as practicable to the natural bed of the river, and in the shallow portion of the American section it is proposed to remove ledge so as to give additional depth of channel for facilitating the discharge of ice.

Computation shows that while the works in the American half of the river are under construction, the open waterway presented by the Canadian half, will afford sufficient discharge capacity for avoiding dangerous heights while the American half of the river is closed by the cofferdam.

After completion of the American half of the bridge and weir, the cofferdam would be removed from the half east of the international boundary, and all gates placed in their lowest position, or set by trial to produce the most favorable conditions for discharge over the American Fall.

The passageway for water through the gates in the American half of the bridge and the channels thence down toward the American Fall can not be made large enough to discharge the total flow in a low season, less the total possible draft through power canals, all down through the American Channel, without throwing too large a quantity down the relatively narrow and shallow channel east of Goat Island and beneath the bridges which connect the small natural islands. Moreover, the wisdom of discharging 10 or 12 feet in depth, required to carry 150 c.f.s. per foot of length, or 150,000 c.f.s. in all, over the 1,000 foot crest of the American Fall, may be questioned, lest so powerful a current dislodge the blocks of fallen rock which presumably protect the base of the American Fall from erosion.

Within the period of unwatering the channel west of Goat Island and while the channel between the head of Goat Island and the American shore, is too narrow for alone carrying the entire normal discharge, less the power draft, a large part of the normal Niagara discharge can be held back temporarily on storage in Lake Erie.

At present it would seem safer to build the Canadian portion of the regulating works and bridge in two stages, or within two successive extensions of cofferdam.

The westerly half of the Canadian section can be enclosed by a transverse cofferdam on its upstream side, joined to a cofferdam parallel to the current passing the upper cascades and thus not wholly depriving the lower reserve power stations of their water supply.

Perhaps this cofferdam parallel with the current and midway of the Canadian section could advantageously be made a permanent feature, if carefully placed to join with the submerged wing dam of the Electrical Development Company's intake, and it could in part be covered by a long irregular series of artificial islands with cascades beween them. These widespread rushing waters, cascading over a series of falls which aggregate 45 feet in height, would present one of the most awe inspiring spectacles of Niagara, if the observer could walk or be seated quietly in the midst of them, as along a pathway down a series of narrow irregular islands, with convenient resting places, to all of which access would be had from the new bridge. At the head of Goat Island the westerly channel is nearly three-quarters of a mile wide.

Various designs for distributing the flow within the region of cascades approaching the Falls can be worked out by the landscape engineer.

While the Canadian part of the works is under construction, or after the works on the Canadian side have been completed, selection would be made of a convenient time of low natural discharge, for unwatering the entire Canadian channel, the cofferdams between the islands being meanwhile continually in place, and the entire discharge, except the power draft, being carried in part in the American Channel, while the surplus beyond the Channel capacity is held back in Lake Erie. The old power houses on the American side, now not regularly operated but held in reserve, might have their water gates opened wide, while the Canadian Channel is being unwatered.

A preliminary estimate (subject to revision after further survey) shows that while unwatering the Canadian Channel temporarily, the depth over the American Fall might safely be increased by 4 or 5 feet (so far as channel east of Goat Island is concerned) which, over its 1,000 feet of crest would increase its discharge to 50,000 c.f.s.

Meanwhile the Power stations in regular service would draw	51,000 c.f.s.
Probably the American reserve stations could draw, say	9,000 c.fs.
Giving a total draft of about	110,000 c.f.s.
Leaving, under average conditions of a total Niagara flow of	207,000 c.f.s.
A surplus beyond channel capacity of about	97,000 c.f.s.
Or say	100,000 c.f.s.

to be held back in storage in Lake Erie, by raising the Canadian regulating gates all to their full height.

Each 1.0 foot in height over the 10,400 sq. miles of Lakes Erie and St. Clair could retain in storage a flow of........100,000 c.f.s. held back for 34 days.

If St. Clair regulation works are complete they could assist in this holding back.

Possibly Lake Erie could be lowered in anticipation of such an unwatering of Canadian Channel for repair of crest, or a season of small natural discharge could be selected for the unwatering and repair of the crest of the Hose Shoe Fall.

After all, it may be more prudent to make provision for not taking more than say 20,000 c.f.s. or the greatest historic quantity over the American Fall lest the blocks of talus at its base be disturbed.

This would give opportunity for building the concrete protection-weir around the notch at the apex of the Horse Shoe Fall, without any further cofferdam and with no danger, under very favorable circumstances, and obviously if any sudden flood or seiche should occur meanwhile so as to necessitate opening more or less of the sluice-ways on the Canadian side in addition to the full opening of all thirty gates on the American side, this could be done without serious injury or important extra cost to the work of repair in progress at the crest of the Horse Shoe Fall. Men, machinery and materials, all could be taken ashore within a very few hours.

It is of interest to compute approximately the quantity of concrete required for levelling up the notch around the apex of the Horse Shoe Fall. If this is done by a sloping massive concrete weir with a rough broken outline, the mass of concrete required for levelling up probably would be equivalent to 600 ft. in total length averaging, say, 12 feet in height (being deeper in the center and less deep at the ends). With crest three feet broad and base of 36 feet, this section would require only about 5,000 cu. yds. of concrete, which probably could be put in place at less than $20.00 per cu. yd. including forms, or a total cost of only about $100,000, instead of the larger part of the $6,000,000 estimated, in the Warren Report, by Lieutenant Jones (see pages 253–284) whose plan necessitated some spectacular cofferdam work and considerable excavation of ledge.

With structural plant made ready in advance, it should be possible to deposit this 5,000 cu. yds of concrete (or double that quantity), by working three 8-hour shifts, and from both ends, within less than 20 days.

Because of the uncertainty as to the precise shape of the deep notch in the Horse Shoe crest prior to its actual unwatering, $200,000 appears a safer estimate of cost in order to cover contingencies.

By thus repairing the damage of recent years, and by preventing its further self-destruction by spreading its water in a broader sheet, and by lessening the present cloud of spray and mist which too largely obscures the view, the Horse Shoe Fall surely can be made far more beautiful than it is now.

THE EXPERIMENTAL MODEL OF NIAGARA FALLS

At least a few words should be said in the present report about the admirably complete working model of the Falls completed under the design and supervision of the late John L. Harper, Chief Engineer of the Niagara Falls Power Company, a few weeks before his untimely death.

This model permits experimental trial of various remedies, for various quantities diverted, while their comparative efficiency is judged.

This model is on a scale of 1 to 100 horizontal and 1 to 25 vertical, and can be made to serve for a great variety of experiments as to the effect of artificial irregular islands near the upper end of Goat Island for redistributing the flow. It also shows the great improvement possible by levelling up the crest.

An hour's observation of experiments with this model while various changes in distribution of water over the crest of the falls are tried out, will convince the most skeptical of the vast improvement in scenic value that can be had by distributing half the present discharge of the Niagara River where it will cover the ends of the Falls and increase the depth on the American Fall in seasons of small natural discharge.

ENLARGING THE CHANNEL AT OUTLET OF LAKE ERIE

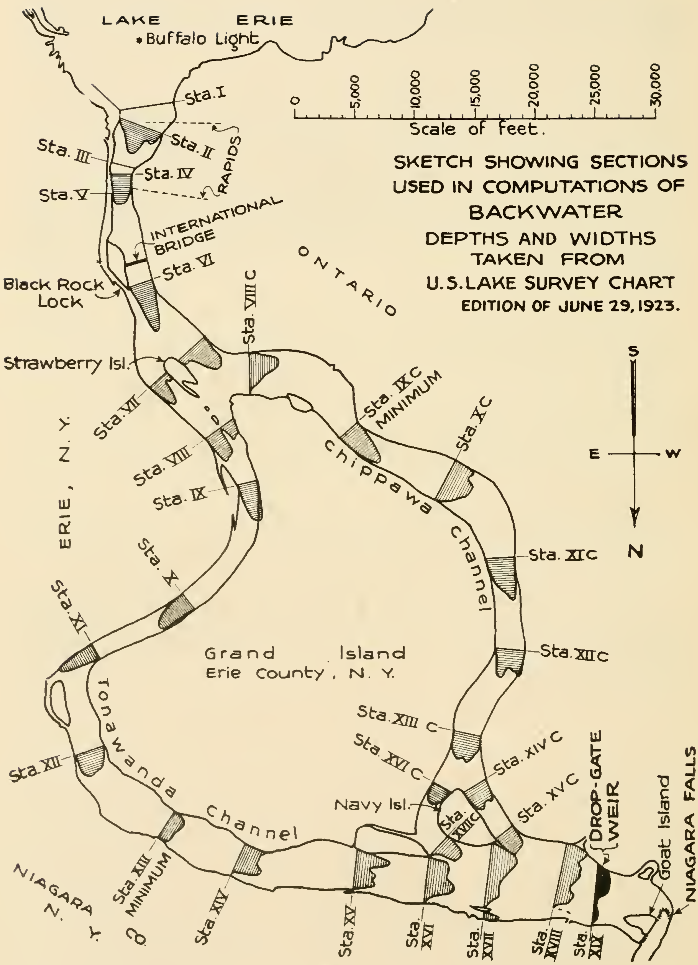
Partly for purpose of future deep-draft-navigation, partly for providing means for running out ice and hastening the opening of Buffalo Harbor, and partly for the purpose of more quickly discharging a surplus from such a severe rainfall as comes only once in a hundred years, and thereby preventing the lakes from rising inconveniently high, it is proposed that at some convenient future time the relatively narrow and shallow outlet of Lake Erie be deepened and widened at the site of the present rapids. These rapids will mostly disappear in the back water from raising the level of the Chippawa Pool, but greater width and depth will become desirable for entrance to the proposed harbor extension 20 miles in length, especially if channels of 25 ft. or 30 ft. depth are opened to the sea.

This work is a long way off and is of indefinite extent until plans for deepwater navigation are fully matured. No estimate of its cost is included, but it would not be large, as harbor improvements go.

NEW BREAKWATER AND ICE BARRIERS IN LAKE ERIE

The present objectionable ice conditions which retard the opening of Buffalo Harbor probably can be remedied by the new breakwaters proposed by Mr. Shenehon and shown in the map on page 256.

These would retain much of the drift-ice until it rotted in place, or until it could be sluiced down the Niagara River and over the Falls, assisted by a judicious use of tugs, and by opening gates in the new regulating works.



LAKE ERIE
Buffalo Light
0 5,000 10,000 15,000 20,000 25,000 30,000
Scale of feet.
SKETCH SHOWING SECTIONS USED IN COMPUTATIONS OF BACKWATER
DEPTHS AND WIDTHS TAKEN FROM U.S. LAKE SURVEY CHART
EDITION OF JUNE 29, 1923.
Sta. I
Sta. II
Sta. III
Sta. IV
Sta. V
RAPIDS
INTERNATIONAL BRIDGE
Sta. VI
Black Rock Lock
ONTARIO
Sta. VIII C
Strawberry Isl.
Sta. VII
Sta. IX C MINIMUM
Sta. X C
S
E
W
N
Sta. VIII
Sta. IX
Chippawa Channel
ERIE, N. Y.
Sta. X
Sta. XI C
Sta. X et XI
Grand Island
Erie County, N. Y.
Sta. XII C
Sta. XIII C
Sta. XVI C
Sta. XIV C
Sta. XII
Tonawanda Channel
Navy Isl.
Sta. XVII C
Sta. XV C
DROP-GATE WEIR
Goat Island
NIAGARA FALLS
NIAGARA N. Y.
Sta. XIII MINIMUM
Sta. XIV
Sta. XV
Sta. XVI
Sta. XVII
Sta. XVIII
Sta. XIX

BACKWATER—CHIPPAWA POOL TO LAKE ERIE

The backwater effect all along from the Chippawa Pool up along the Niagara River through both channels, past Tonawanda Harbor and the entrance to the Erie Canal, has been very carefully estimated anew, from the excellent data obtained in surveys made in 1911 and 1912 for the purposes of the second report of the International Waterways Commission, precedent to working out its design for the submerged weir, between Welland River and Gill Creek, proposed in their report of 1913. The back-water profiles, coefficients, etc., computed from the data of the International Commission, are shown in condensed form in the diagrams and tables which follow.

So far as backwater is concerned, and so far as regards the production of a sufficient increase of height for navigation and storage in Lake Erie, by means of raising the Chippawa Pool which is 20 miles downstream from the Lake, **these backwater computations demonstrate the feasibility of this project.**

The effect in raising Lake Erie corresponding to a given rise at Chippawa is found to be as given in the following table. Obviously, the elevation of Chippawa Pool could be placed at any desired stage other than those shown in this table. The method of computation is explained in the pages that follow.

The following computation of back water effect, from Chippawa Pool to Lake Erie, takes things as they now are, and does not allow for the effect of possible future enlargements of this "neck-of-the-bottle;" mentioned on the preceding page, all of which effects will be favorable to regulation.

The discharges of 377,000, 209,000 and 153,000 c.f.s. represented by lines on the following profiles and used for representative conditions of high average and low flow were those used for representative stages in the report of 1913 and are used here for convenience of comparison of present with former estimates of backwater effect.

Under **an average annual discharge** of 209,000 cu. ft. sec., for which the present normal elevation in Chippawa Pool at intake is 562.0, the effect upon Lake Erie of raising the Chippawa Pool would be as follows:

		From	To
A rise of 5 feet at Chippawa raises Lake Erie	0.75 ft.	572.6	573.35
" " " 6 " " " " " "	1.05 "	"	573.65
" " " 7 " " " " " "	1.50 "	"	574.10
" " " 8 " " " " " "	1.95 "	"	574.55

For the proposed **future minimum discharge** of 180,000 c.f.s., for which the present normal elevation in Chippawa Pool is 561.25, the effect is as follows:

		From	To
A rise of 5 feet at Chippawa raises Lake Erie	0.80 ft.	571.3	572.1
" " " 7 " " " " " "	1.55 "	"	572.8
" " " 8 " " " " " "	2.00 "	"	573.3
" " " 9 " " " " " "	2.50 "	"	573.8
" " " 10 " " " " " "	3.10 "	"	574.4

This rise in Erie would extend back into the Detroit River and aid its navigation depths.

BACKWATER IN LAKE ERIE FROM PROPOSED WEIR

Discharge from Lake Erie c.f.s.	Normal Elev. in Chippawa Pool at Weir	Regulated Elevation in Chippa-wa Pool	Rise in Chippawa Pool Feet	Regulated Elevation in Lake Erie	Normal Unregulated Elevation in Lake Erie	Back Water Effect upon Lake Erie
250,000	563.0	565.0	2.0	574.45	574.2	0.25
		566.0	3.0	574.65	574.2	0.45
209,000	562.0	567.0	5.0	573.35	572.6	0.75
		568.0	6.0	573.65	572.6	1.05
		569.0	7.0	574.0	572.6	1.40
		570.0	8.0	574.5	572.6	1.90
180,000	561.3	570.0	8.7	573.6	571.3	2.30
		571.0	9.7	574.2	571.3	2.90
		572.0	10.7	574.9	571.3	3.60
153,000	560.6	570.0	9.4	572.75	570.0	2.75
		571.0	10.4	573.4	570.0	3.40
		572.0	11.4	574.2	570.0	4.20

Thus it is seen that for a high regulated stage of the river (209,000 c.f.s.) the weir gates will be required to raise the Chippawa Pool only 8.0 feet to produce the proposed maximum regulated high water of 574.5 in Lake Erie.

For the minimum regulated stage of the river (180,000 c.f.s.) Chippawa Pool would be raised about 10.1 feet.

The smaller the discharge, the greater the amount by which the Chippawa Pool will need to be raised, because of the lessened loss by hydraulic friction, or slope, within the 20 miles of river. Thus it happens that the head against the proposed shallow dike extending from the regulating works upstream to Tonawanda will be smallest in time of discharge of great floods.

CHIPPAWA TO ERIE BACKWATER COMPUTATIONS

The following profiles, tables and diagrams give in briefest form the data and the successive steps in the computations of the back-water effect of the proposed regulation works, and show the height at which the Chippawa Pool must be held with various quantities flowing in the upper Niagara River, in order to produce a desired elevation in Lake Erie.

In case there should be found any discrepancy between the computed and the actual results, no harm will result. It will merely be necessary to slightly raise or lower some of the gates, and adjust the height in the Chippawa Pool until the desired relation is obtained. Experience will soon determine the proper adjustments for wind effects or ice.

The following 8 profiles, diagrams and tables need little explanation to engineers experienced in this kind of estimation.

The first important step is to obtain the coefficient of flow "C", for the several portions of the irregular channel around Grand Island.

The second step is to use the coefficients thus obtained for computing the river slope under the new conditions of depth and velocity.

The final diagram of Relation of Elevation in Lake Erie to Elevation in Chippawa Pool, presented on page 309, condenses a large amount of information about these relations into small compass and may be used for other elevations or quantities than those given in the tables above.

For making these computations the coefficients of channel resistance at various depths were carefully worked out from the following data. Mean depths and areas of channel were obtained by scaling cross-sections drawn from depths given on U. S. Lake Survey Chart for standard low water, which takes Lake Erie at El. 570.0 and discharge 153,000 c.f.s. Surface at weir-site, El. 560.5.

The very carefully measured water profiles surveyed for the International Waterways Commission in 1911 were taken as the starting point.

Natural water elevations were obtained by scaling profiles on International Waterways Report Plates III and IV. The natural Profile for 250,000 c.f.s. was interpolated between profiles for 209,000 and 377,000 c.f.s.

The slope used in the Chezy formula was determined from the observed slope by allowing for velocity head, and assuming recoveries of head, where velocity decreased, only from 50 to 70%, depending upon conditions, shape and curvature of channel.

The subdivision between the Chippawa and Tonawanda Channels was carefully proportioned to 4% greater hydraulic radius plus 15% greater slope and 35% greater area in Chippawa Channel; from which it was deduced that 62% of whole volume of flow passes through the Chippawa Channel. Similarly it was computed that 57% of the Chippawa Channel discharge passed west of Navy Island.

Later it was noted that in the current meter gagings of the Niagara River in 1913, the discharges found in these two channels were respectively

In Tonawanda Channel	91,900 c.f.s. or 42 %
In Chippawa Channel	124,900 c.f.s. or 58 %
Total	216,800 c.f.s. or 100 %

In other words, these current meter gagings showed 58 % actually passing down the Chippawa Channel instead of the 62% deduced from channel depths and derived coefficients of fluid friction. This fairly close agreement serves to confirm accuracy of methods of computation used, and results of backwater effect deduced in the preceding table.

Explanation of Tables and Diagrams

The map on page 294 shows the channels between the outlet of Lake Erie and the regulation works within which the back-water is to be estimated for various rates of river discharge and for various elevations of Chippawa Pool, as fixed by closing of regulating gates to a greater or a less extent.

The diagrams on pages 301 and 302 show the water profiles under natural, or present conditions, for widely different rates of discharge, as determined by the extensive and precise surveys of the International Waterways Commission in 1911 and 1912.

The table on pages 301 and 303 give the principal data and the several steps in the somewhat difficult problem of determining the coefficient of flow in these irregular channels, mainly from data presented in diagrams on pages 301 and 302.

The diagram on page 304 shows graphically the magnitude of the coefficients as computed by the formula $V = C\sqrt{RS}$, which are found in tolerably good agreement with each other and with what one would expect in this kind of channel.

Next follow tables of backwater computation by means of the coefficients and other data of the preceding tables and diagrams.

The diagram on page 308 gives the water profiles found by these computations, for various representative rates of discharge and shows the backwater effect from holding the Chippawa Pool at various elevations. It will be noted that **the rapids in the gorge at the head of the river become largely drowned out by backwater from the raised Chippawa Pool.**

On page 309 is a complicated diagram which sums up the results of the preceding computations in form of a series of curves, which by interpolation will give the backwater effect and the resulting elevation in Lake Erie for any elevation in Chippawa Pool, and for any rate of flow, within ordinary limits.

The principal coordinates horizontally represent elevations in the Chippawa Pool and vertically the elevations in Lake Erie.

Obviously, the slope and elevation within the 20 miles of channel will vary with the rate of discharge from Lake Erie. The straight inclined line at the left shows the relation of elevation in Chippawa Pool to that in Lake Erie under natural conditions, as observed in 1911-12 when a somewhat smaller amount of water for power development was being taken out of the Chippawa Pool than at present.

In general, it is seen that while Lake Erie under natural conditions rises 3.0 feet or from El. 571 to El. 574. the Chippawa Pool rises from El. 561.08 to El. 562.75, or only 1.57 ft., or about one-half as much as Erie. However, it must be remembered that under these natural unregulated conditions the discharge changes with each change in the elevation of Lake Erie, and that for a rise from El. 571 to El. 574, the discharge would increase 66,000 c.f.s., or from 175,000 to 241,000 c.f.s.

From points along this straight inclined line other smaller diagrams branch off enclosing spaces between a curved top line and a straight base line.

Each of these 5 subsidiary diagrams shows the backwater caused, at a stated rate of discharge (respectively 153,000 c.f.s. 180,000 c.f.s., 209,000 c.f.s., 250,000 c.f.s. and 300,000 c.f.s.) by raising Chippawa Pool to various levels.

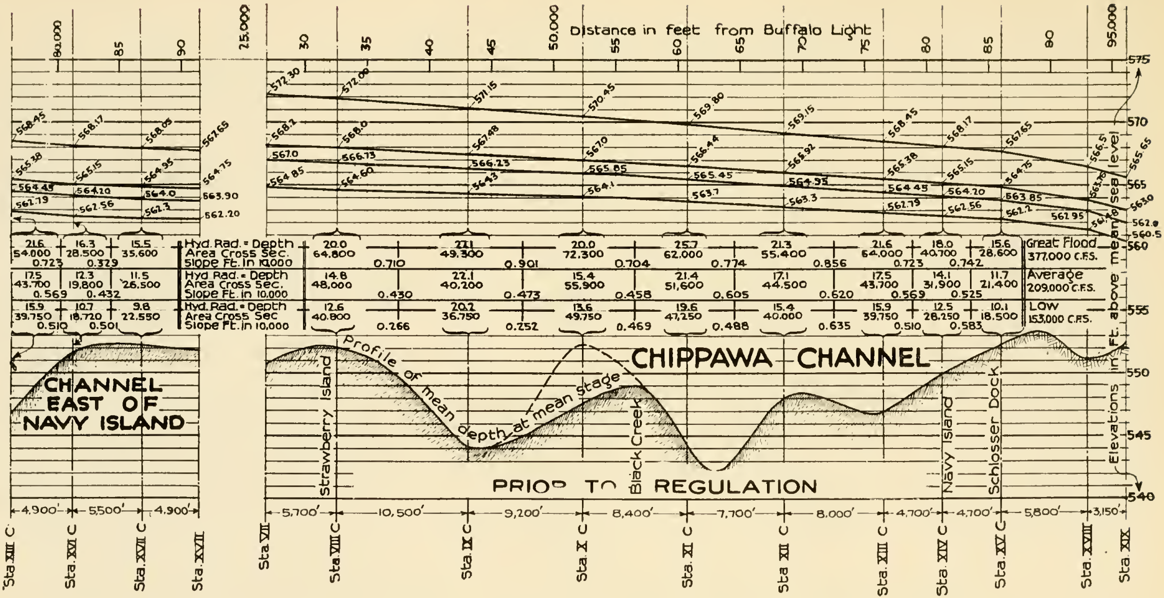
Each of these subsidiary diagrams, obviously, must have its origin on the inclined straight line of relations of lake elevation at the point, or elevation in Lake Erie, at which this quantity would be discharged from Lake Erie.

As Chippawa Pool is raised while rate of discharge remains unchanged Lake Erie will be raised to the elevation shown by the curved line at its intersection with the co-ordinate line corresponding to the elevation in the Chippawa Pool.

The amount by which raising the Chippawa Pool raises Lake Erie is shown to the same scale by the length of the intercept between the curve and its horizontal base.

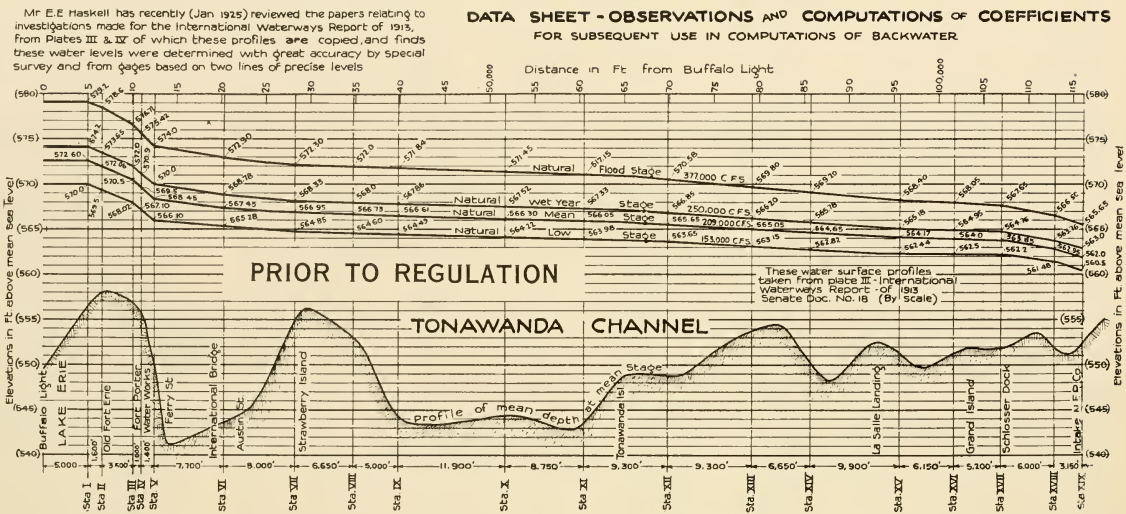
Obviously, interpolation can give heights in Erie, or amount of backwater caused, at any other rate of discharge or any other height in Chippawa Pool.

It was by this diagram that the heights due backwater for various conditions, presented on page 296, were obtained.



PROFILE OF WATER SURFACE IN CHIPPAWA CHANNEL FOR VARIOUS STAGES

From Surveys for International Waterways Commission, 1910–1913



PROFILE OF WATER SURFACE ALONG NIAGARA RIVER FOR VARIOUS STAGES

From Surveys for International Waterways Commission, 1910–1913

Great Flood — Discharge 372,000 c.f.s.

Station	Mean depth at Sta (Ft)	Width (Ft)	Mean Vel at Sta (Ft/Sec)
Sta I	22.5	4,600	3.64
Sta II	20.6	3,770	4.85
Sta III	19.9	2,000	9.48
Sta IV	19.7	1,660	11.52
Sta V	24.0	1,600	9.82
Sta VI	29.2	1,850	6.98
Sta VII	20.0	4,780	3.94
Sta VIII	19.1	2,780	2.71
Sta IX	27.3	1,660	3.18
Sta X	26.9	1,760	3.04
Sta XI	27.6	1,480	3.53
Sta XII	21.8	2,570	2.57
Sta XIII	16.2	2,700	3.30
Sta XIV	19.1	2,630	2.86
Sta XV	17.0	3,260	2.60
Sta XVI	16.8	3,680	2.33
Sta XVII	15.9	6,240	2.46
Sta XVIII	14.2	5,700	4.65
Sta XIX	13.6	5,020	5.52

Between Stas	Diff in surface Elev (Ft)	PC Vel head recovered	Correction for Vel Hd (Ft)	Friction head (Ft)	Dist between Stas (Ft)	Slope (Ft in 10,000)	Mean Hyd Rad Betw Stas	Mean Velocity (Ft/Sec)	Computed Value of C
I–II	0.60	–	–	.440	1,600	2.75	21.5	4.24	55
II–III	1.89	–	–	.861	3,500	2.46	20.2	7.16	101
III–IV	1.26	–	–	.590	1,000	5.9	19.8	10.50	98
IV–V	1.05	50	+.285	1.335	1,400	9.54	21.8	10.62	75
V–VI	1.50	50	+.368	1.868	7,700	2.425	26.6	8.40	104
VI–VII	0.60	60	+.321	.921	8,000	1.15	24.6	5.46	103
VII–VIII	0.30	60	+.049	.349	6,170	.567	19.8	3.57	106
VIII–IX	0.16	–	–	.117	5,000	.234	23.2	2.94	126
IX–X	0.29	50	+.006	.296	11,900	.249	27.1	3.11	120
X–XI	0.30	–	–	.250	8,750	.286	27.2	3.28	118
XI–XII	0.57	50	+.045	.615	9,300	.661	24.7	3.05	75
XII–XIII	0.78	–	–	.714	9,300	.768	19.0	2.93	77
XIII–XIV	0.60	70	+.029	.629	6,650	.946	17.6	3.08	76
XIV–XV	0.80	70	+.015	.815	9,900	.822	18.0	2.73	71
XV–XVI	0.35	70	+.015	.365	6,150	.594	16.9	2.46	78
XVI–XVII	0.40	60	+.002	.402	5,050	.795	16.1	2.48	107
XVII–XVIII	1.15	–	–	.949	5,900	1.61	15.1	3.80	77
XVIII–XIX	0.85	–	–	.715	3,150	2.263	13.9	5.08	91

Extra wet month — Discharge 250,000 c.f.s.

Station	Mean depth at Sta (Ft)	Width (Ft)	Mean Vel at Sta (Ft/Sec)
Sta I	17.7	4,600	3.07
Sta II	15.7	3,770	4.22
Sta III	15.2	2,000	8.22
Sta IV	15.1	1,660	9.97
Sta V	19.6	1,600	7.96
Sta VI	25.1	1,850	6.28
Sta VII	15.9	4,870	3.29
Sta VIII	15.0	2,780	2.32
Sta IX	23.4	1,660	2.44
Sta X	23.0	1,760	2.35
Sta XI	23.6	1,480	2.72
Sta XII	18.1	2,570	2.04
Sta XIII	12.5	2,700	2.81
Sta XIV	15.6	2,630	2.32
Sta XV	13.7	3,260	2.13
Sta XVI	13.6	3,680	1.90
Sta XVII	12.9	6,240	2.01
Sta XVIII	11.5	5,700	3.81
Sta XIX	10.1	5,070	4.92

Between Stas	Diff in Surface Elev (Ft)	P.C. Vel head recovered	Correction for Vel Hd (Ft)	Friction head (Ft)	Dist between Stas (Ft)	Slope (Ft in 10,000)	Mean Hyd Rad Betw Stas	Mean Velocity (Ft/Sec)	Computed Value of C
I–II	0.55	–	–.131	0.415	1,600	2.62	16.7	3.64	55
II–III	1.65	–	–.773	.877	3,500	2.50	15.4	6.22	100
III–IV	1.10	–	–.491	.609	1,000	6.09	15.1	9.09	99
IV–V	0.90	50	+.278	1.178	1,400	8.42	17.3	8.96	75
V–VI	1.22	50	+.186	1.406	7,700	1.825	22.3	7.12	112
VI–VII	0.45	60	+.267	.717	8,000	0.896	20.5	4.78	111
VII–VIII	0.33	60	+.034	.364	6,170	0.59	15.6	2.99	99
VIII–IX	0.14	–	–	.131	5,000	0.26	19.2	2.38	106
IX–X	0.34	50	+.003	.343	11,900	0.29	23.2	2.39	92
X–XI	0.29	–	–	.261	8,750	0.30	23.3	2.53	96
XI–XII	0.48	50	+.025	.505	9,300	0.54	20.8	2.38	71
XII–XIII	0.65	–	–	.592	9,300	0.64	15.3	2.42	77
XIII–XIV	0.42	70	+.027	.447	6,650	0.67	14.0	2.56	84
XIV–XV	0.60	70	+.009	.609	9,900	0.61	14.6	2.22	74
XV–XVI	0.23	70	+.010	.240	6,150	0.39	13.6	2.01	87
XVI–XVII	0.20	60	+.002	.202	5,050	0.40	13.0	2.02	88
XVII–XVIII	0.99	–	–	.853	5,900	1.447	12.1	3.115	74
XVIII–XIX	0.76	–	–	.61	3,150	1.985	10.8	4.36	95

Average — Discharge 209,000 c.f.s.

Station	Mean depth at Sta (Ft)	Width (Ft)	Mean Vel at Sta (Ft/Sec)
Sta I	16.0	4,600	7.84
Sta II	14.1	3,770	3.94
Sta III	13.7	7,000	7.62
Sta IV	13.6	1,660	9.24
Sta V	18.0	1,600	7.25
Sta VI	23.8	1,850	4.75
Sta VII	17.6	4,870	3.46
Sta VIII	13.8	2,780	2.06
Sta IX	21.8	1,660	2.18
Sta X	21.8	1,760	2.06
Sta XI	72.5	1,480	2.37
Sta XII	16.9	2,570	1.82
Sta XIII	11.4	2,700	2.56
Sta XIV	14.5	2,630	2.06
Sta XV	12.7	3,260	1.91
Sta XVI	12.7	3,680	1.69
Sta XVII	12.1	6,240	1.83
Sta XVIII	10.6	5,[illegible]00	3.46
Sta XIX	9.1	5,020	4.57

Between Stas	Diff in surface Elev (Ft)	PC Vel. head recovered	Correction for Vel Hd (Ft)	Friction head	Distance between Stas (Ft)	Slope (Ft in 10,000)	Mean Hyd Rad Betw Stas	Mean Velocity (Ft/Sec)	Computed Value of C
I–II	0.55	–	–	.434	1,600	2.71	15.0	3.39	53
II–III	1.55	–	–	.889	3,500	2.54	13.9	5.78	98
III–IV	1.00	–	–	.577	1,000	5.77	13.6	8.43	96
IV–V	1.05	50	+.254	1.304	1,400	9.32	15.8	8.24	68
V–VI	1.00	50	+.233	1.233	7,700	1.60	20.9	6.00	104
VI–VII	0.50	60	+.104	.604	8,000	0.755	18.2	4.10	110
VII–VIII	0.22	60	+.057	.277	6,170	0.449	13.4	2.94	120
VIII–IX	0.12	–		.112	5,000	0.224	17.8	2.12	106
IX–X	0.31	50	+.004	.314	11,900	0.260	21.8	2.12	89
X–XI	0.25	–	–	.229	8,750	0.260	22.1	2.21	92
XI–XII	0.40	50	+.018	.418	9,300	0.450	19.7	2.09	70
XII–XIII	0.60	–	–	.549	9,300	0.590	14.1	2.19	77
XIII–XIV	0.40	70	+.025	.425	6,650	0.640	12.9	2.31	81
XIV–XV	0.48	70	+.006	.589	9,900	0.494	13.6	1.98	77
XV–XVI	0.17	70	+.009	.179	6,150	0.291	12.7	1.80	94
XVI–XVII	0.15	60	+.001	.151	5,050	0.299	12.2	1.82	95
XVII–XVIII	0.90	–	–	.800	5,900	1.35	11.3	2.82	72
XVIII–XIX	0.95	–	–	.812	3,150	2.420	9.8	4.01	80

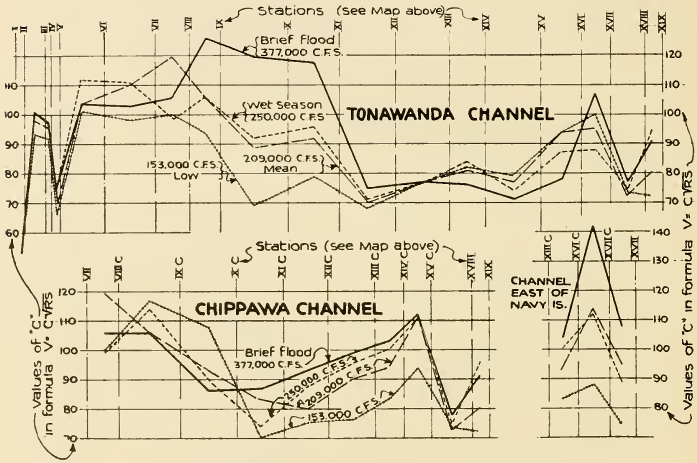
Low — Discharge 153,000 c.f.s.

Station	Mean depth at Sta (Ft)	Width (Ft)	Mean Vel. at Sta (Ft/Sec)
Sta I	13.4	4,600	2.48
Sta II	11.6	3,770	3.50
Sta III	11.2	2,000	6.83
Sta IV	11.2	1,660	8.23
Sta V	15.7	1,600	6.09
Sta VI	21.6	1,850	3.82
Sta VII	12.5	4,870	2.56
Sta VIII	11.7	2,780	1.78
Sta IX	20.0	1,660	1.75
Sta X	19.7	1,760	1.68
Sta XI	20.4	1,480	1.92
Sta XII	14.9	2,570	1.51
Sta XIII	9.5	2,700	2.26
Sta XIV	12.7	2,630	1.74
Sta XV	11.0	3,260	1.62
Sta XVI	11.0	3,680	1.43
Sta XVII	10.4	6,240	1.52
Sta XVIII	9.2	5,700	2.91
Sta XIX	7.6	5,020	4.00

Between Stas	Diff in surface Elev. (Ft)	PC Vel head recovered	Correction for Vel Hd (Ft)	Friction head (Ft)	Dist between Stas (Ft)	Slope (Ft in 10,000)	Mean Hyd Rad Betw Stas	Mean Velocity (Ft/Sec)	Computed Value of C
I–II	0.50	–	–	.406	1,600	2.54	12.5	2.99	53
II–III	1.48	–	–	.946	3,500	2.70	11.4	5.16	93
III–IV	0.92	–	–	.590	1,000	5.90	11.2	7.53	92
IV–V	1.00	50	+.239	1.239	1,400	8.85	13.4	7.16	66
V–VI	0.82	50	+.174	.994	7,700	1.29	18.6	4.95	101
VI–VII	0.43	60	+.075	.905	8,000	.622	17.0	3.19	98
VII–VIII	0.25	60	+.020	.270	6,170	.438	12.3	2.32	100
VIII–IX	0.11	50	+.001	.111	5,000	.222	15.8	1.77	94
IX–X	0.37	50	+.002	.372	11,900	.312	19.8	1.71	69
X–XI	0.24	–	–	.226	8,750	.259	20.0	1.80	79
XI–XII	0.33	50	+.012	.342	9,300	.368	17.6	1.71	68
XII–XIII	0.50	–	–	.456	9,300	.450	12.2	1.88	77
XIII–XIV	0.33	70	+.023	.353	6,650	.531	11.1	2.00	82
XIV–XV	0.38	70	+.004	.384	9,900	.388	11.8	1.68	79
XV–XVI	0.14	70	+.006	.146	6,150	.237	11.0	1.52	94
XVI–XVII	0.010	60	+.0014	.0114	5,050	.226	10.4	1.54	100
XVII–XVIII	0.72	–	–	.6403	5,900	1.085	9.7	2.37	73
XVIII–XIX	0.98	–	–	.863	2,420	2.740	8.4	3.45	72

THE ABOVE TABLE GIVES DETAILED COMPUTATION FOR VALUES OF C FOR THE 4 PROFILES GIVEN ON THE PRECEDING PAGE

The diagram below shows in a form convenient for comparisons the values of coefficients of channel resistance for the Chezy Formula, deduced for various river stages in the preceding tables on pages 301 and 303, from the profiles of the International Commission and the sectional areas and distances shown on the Lake Survey Charts and given on the above pages.



COEFFICIENTS "C" IN "$V=C\sqrt{RS}$"

Computed from observed heights, depths and areas at sections shown on map above—for maximum, mean and minimum stages—for use in computing backwater.

BACKWATER COMPUTATIONS, CHIPPAWA POOL TO LAKE ERIE

BACKWATER TABLE I — HIGH DISCHARGE

Data from which elevations for backwater curves were computed by successive approximations. **FOR TONAWANDA CHANNEL**

Discharge from Lake Erie 250,000 C.F.S. — Chippawa Pool held at Elev. 567.0

Station	Discharge Q	Area of channel cross section A	Corresp. mean velocity at Station $V=\frac{Q}{A}$	Between Stations: Mean Velocity V'	Mean Hyd. Radius R	Value of C used	Slope of water Surface due to friction $S=\left(\frac{V'}{C}\right)^2\frac{1}{R}$	Distance between Stations L	Friction Head	Correction for Diff. in Vel. heads: P. C. Asmd Recvd	Correction for Diff. in Vel. heads	Computed difference in Elev. of water Surface	Surface elevations at Stations found by computations
	C.F.S.	Sq. Ft.	Ft per Sec.	Ft per Sec.			In 10,000 Ft.	Ft.	Ft.	%	Ft.	Ft.	Ft above sea
XIX	250,000	70,900	3.52										567.00
				3.21	14.6	91	0.865	3.150	0.270	—	+.062	0.33	
XVIII	"	86.000	2.91										567.33
				2.66	15.6	72	.935	5.900	.632	—	+.073	.71	
XVII + XV C	"	129,000	2.41										568.04
XVII	161,500	100,000	1.60										568.04
				1.62	16.2	98	.172	5.050	.087	—	+.016	.10	
XVI + XVII C	"	98,150	1.64										568.14
XVI	95,000	62,100	1.53										568.14
				1.62	16.6	78	.280	6.150	.172	70	-.003	.17	
XV	"	55,000	1.72										568.31
				1.79	18.1	71	.350	9.900	.346	70	-.005	.35	
XIV	"	51,350	1.85										568.68
				2.07	17.4	76	.426	6.650	.284	70	-.020	.26	
XIII	"	41,450	2.29										568.92
				2.04	17.9	77	.393	9.300	.366	–	+.032	.40	
XII	"	52,900	1.80										569.32
				2.13	23.2	75	.348	9.300	.323	50	-.022	.30	
XI	"	38,500	2.46										569.62
				2.30	25.6	118	.147	8.750	.130	–	+.023	.15	
X	"	44,400	2.14										569.77
				2.19	25.3	106	.169	11.900	.201	50	-.004	.20	
IX	"	42,300	2.24										569.77
				2.11	21.3	116	.155	5.000	.078	–	+.016	.09	
VIII	"	47,650	1.99										570.06
VIII + VIII C	250,000	106,200	2.36										570.06
				2.64	17.7	102	.379	6.170	.233	60	-.034	.20	
VII	"	85,650	2.92										570.26
				3.96	22.4	107	.612	8,000	.490	60	-.153	.34	
VI	"	49,950	5.00										570.60
				6.22	24.0	108	1.380	7,700	1.055	50	-.236	.82	
V	"	33,600	7.44										571.42
				8.34	18.6	75	6.650	1,400	.930	50	-.235	.70	
IV	"	27,000	9.25										572.12
				8.49	16.1	98	4.650	1,000	.465	–	+.400	.86	
III	"	32,300	7.74										572.98
				5.88	16.3	100	2.120	3,500	.742	–	+.679	1.42	
II	"	62,200	4.02										574.40
				3.50	17.4	55	2.320	1,600	.372	–	+.114	.49	
I	"	84,100	2.97										574.85

BACKWATER TABLE II — HIGH DISCHARGE

Data from which elevations for backwater curves were computed by successive approximations. **FOR CHIPPAWA CHANNEL**

Discharge from Lake Erie 250,000 C.F.S. — Chippawa Pool held at Elev. 567.0

Station	Discharge Q	Area of channel cross section A	Corresp. mean velocity at Station $V=\frac{Q}{A}$	Between Stations: Mean Velocity V'	Mean Hyd. Radius R	Value of C used	Slope of water Surface due to friction $S=\left(\frac{V'}{C}\right)^2\frac{1}{R}$	Distance between Stations L	Friction Head	Correction for Diff. in Vel. heads: P.C. Asmd Recvd	Correction for Diff. in Vel. heads	Computed difference in Elev. of water surface	Surface elevations at stations found by computations
	C.F.S	Sq. Ft	Ft per Sec.	Ft per Sec			In 10,000 Ft.	Ft.	Ft.	%	Ft.	Ft.	Ft. above sea
XV C	88,500	29,400	2.91										568.04
				2.49	17.15	112	0.29	4,700	0.136	–	+.064	0.20	
XIV C	"	41,100	2.08										568.24
XIV C + XVI C	"	69,770	2.22										568.24
				2.55	19.4	103	.317	4,700	.149	60	-.032	.12	
XIII C	155,000	53,700	2.87										568.36
				2.87	21.15	99	.400	8,000	.320	–	+.001	.32	
XII C	"	54,050	2.88										568.68
				2.72	22.85	93	.377	7,700	.290	–	+.025	.32	
XI C	"	60,000	2.58										569.00
				2.42	21.91	85	.369	8,400	.310	–	+.024	.33	
X C	"	68,750	2.25										569.33
				2.79	22.2	88	.453	9,200	.417	70	-.065	.35	
IX C	"	46,550	3.33										569.68
				2.99	21.8	114	.315	10,500	.330	–	+.063	.39	
VIII C	"	58,500	2.65										570.07
FOR SECTION OF CHANNEL EAST OF NAVY ISLAND													
XVII C	66,500	36,000	1.85										568.14
				2.08	15.9	112	.207	5,500	.120	70	-.020	.10	
XVI C	"	28,670	2.32										568.24

BACKWATER TABLE III — AVERAGE DISCHARGE

Data from which elevations for backwater curves were computed by successive approximations. **FOR TONAWANDA CHANNEL**

Discharge from Lake Erie - 209,000 C.F.S. Chippawa Pool held at Elev 567.0

Station	Discharge Q	Area of channel cross section A	Corresp. mean velocity at Station $V=\frac{Q}{A}$	Between Stations: Mean velocity V'	Mean Hyd. Radius R	Value of C used	Slope of Water Surface due to friction $S=\left(\frac{V'}{C}\right)^2\frac{1}{R}$	Distance between Stations L	Friction Head	Correction for Diff in Vel heads: P.C. Asmd. Recvd.	Correction for Diff in Vel heads	Computed difference in Elev of water Surface	Surface elevations at Stations found by computations.
	C.F.S.	Sq. Ft.	Ft per Sec.	Ft per Sec			In 10,000 Ft.	Ft	Ft	%	Ft.	Ft	Ft above Sea
XIX	209,000	70,900	2.95										567.0
				2.70	16.7	91	0.529	3,150	0.167	–	+.042	0.21	
XVIII	"	85,200	2.46										567.21
				2.18	15.3	77	.523	5,900	.523	–	+.051	.36	
XVII + XV C	"	126,700	1.65										567.57
XVII	135,000	98,400	1.37										567 57
				1.40	15.8	107	.108	5,050	.054	60	–.001	06	
XVI + XVII C	"	94,950	1.42										567.63
XVI	79,000	59,800	1.32										567 63
				1.40	16.3	78	.199	6,150	.123	70	–.005	.12	
XV	"	53,200	1.49										567.75
				1.59	17.1	71	.293	9,900	.290	70	–.007	.28	
XIV	"	46,900	1.69										568.03
				1.85	16.2	76	.367	6,650	.244	70	–.013	.23	
XIII	"	39,450	2.01										568.26
				1.78	17.2	77	.311	9,300	.290	–	+.026	.32	
XII	"	51,000	1.55										568.58
				1.83	22.5	73	.280	9,300	.260	50	–.003	.26	
XI	"	37,400	2.11										568.84
				1.97	24.8	100	.157	8,750	.138	–	+.017	.16	
X	"	43,000	1.84										569.00
				1.88	24.6	101	.142	11,900	.169	50	–.002	.17	
IX	"	41,000	1.93										569.17
				1.83	20.5	116	.122	5,000	.061	–	+.009	.07	
VIII	"	45,450	1.74										569.24
VIII + VIII C	209,000	101,200	2.07										569.24
				2.31	16.9	100	.317	6,170	.195	60	–.022	.17	
VII	"	81,600	2.56										569.41
				3.45	21.6	110	.467	8,000	.356	60	–.115	.24	
VI	"	48,200	4.34										569.65
				5.35	23.5	104	1.125	7,700	.867	50	–.167	.70	
V	"	32,900	6.35										570.35
				7.38	17.8	75	5.540	1,400	.761	50	–.230	.53	
IV	"	24,900	8.40										570.88
				7.73	14.9	98	4.180	1,000	.418	–	+.320	.74	
III	"	29,600	7.06										571.62
				5.38	14.9	100	1.950	3,500	.684	–	+.562	1.25	
II	"	56,400	3.71										572.87
				3.21	15.8	53	2.320	1,600	.371	–	+.098	.47	
I	"	76,900	2.72										573.34

BACKWATER TABLE IV — MEDIUM LOW DISCHARGE

Data from which elevations for backwater curves were computed by successive approximations. **FOR TONAWANDA CHANNEL**

Discharge from Lake Erie 180,000 C.F.S. Chippawa Pool held at Elev. 567.0

Station	Discharge Q	Area of channel cross section A	Corresp. mean velocity at Station $V=\frac{Q}{A}$	Between Stations: Mean Velocity V'	Mean Hyd. Radius R	Value of C used	Slope of water Surface due to friction $S=\left(\frac{V'}{C}\right)^2\frac{1}{R}$	Distance between Stations L	Friction Head.	Correction for Diff. in Vel. heads: P.C. Asmd Recvd	Correction for Diff. in Vel. heads	Computed difference in Elev of water Surface.	Surface elevations at Stations found by computations.
	C.F.S.	Sq. Ft.	Ft. per Sec.	Ft. per Sec			In 10,000 Ft.	Ft.	Ft.	%	Ft.	Ft.	Ft above sea
XIX	180,000	70,900	2.54										567.0
				2.33	15.9	91	0.409	3,150	0.132	–	+.014	0.15	
XVIII	"	84,900	2.12										567.15
				1.78	15.3	77	.348	5,900	.206	–	+.044	.25	
XVII + XV C	"	125,500	1.44										567.40
XVII	116,500	97,400	1.20										567.44
				1.21	15.7	107	.083	5,050	.042	60	–.001	.04	
XVI + XVII C	"	94,000	1.23										567.44
XVI	68,500	59,500	1.15										567.44
				1.23	16.1	78	.153	6,150	.094	70	–.004	.19	
XV	"	52,450	1.31										567.53
				1.39	16.9	71	.228	9,900	.225	70	–.005	.22	
XIV	"	46,300	1.48										567.75
				1.63	15.9	76	.290	6,650	.190	70	–.010	.18	
XIII	"	38,500	1.78										567.93
				1.58	16.8	77	.250	9,300	.230	–	+.020	.25	
XII	"	49,900	1.37										568.18
				1.62	22.1	71	.236	9,300	.220	50	–.010	.21	
XI	"	36,700	1.87										568.39
				1.74	24.4	105	.113	8,750	.099	–	+.013	.11	
X	"	42,200	1.62										568.50
				1.71	23.5	104	.116	11,900	.139	50	–.005	.13	
IX	"	38,000	1.80										568.63
				1.68	19.4	114	.112	5,000	.056	–	+.013	.07	
VIII	"	43,900	1.56										568.70
VIII + VIII C	180,000	98,000	1.84										568.70
				2.06	16.4	110	.214	6,170	.132	60	–.017	.12	
VII	"	78,900	2.28										568.82
				3.06	20.9	110	.370	8,000	.296	60	–.090	.21	
VI	"	46,900	3.84										569.03
				4.85	22.3	104	.975	7,700	.750	50	–.150	.60	
V	"	30,800	5.85										569.63
				6.70	16.8	70	5.450	1,400	.762	50	–.179	.58	
IV	"	23,800	7.56										570.21
				7.01	14.2	97	3.680	1,000	.368	–	+.246	.60	
III	"	28,000	6.43										570.81
				4.92	14.0	98	1.805	3,500	.632	–	+.463	1.10	
II	"	52,800	3.41										571.91
				2.95	14.8	53	2.090	1,600	.334	–	+.085	.42	
I	"	61,700	2.49										572.33

BACKWATER TABLE V — LOW DISCHARGE

Data from which elevations for backwater curves were computed by successive approximations **FOR TONAWANDA CHANNEL**

Discharge from Lake Erie 153,000 C.F.S. Chippawa Pool held at Elev. 567.0

Station	Discharge Q	Area of Channel cross section A	Corresp. mean velocity at Station $V=\frac{Q}{A}$	Between Stations: Mean Velocity V'	Mean Hyd. Radius R	Value of C used	Slope of water Surface due to friction $S=\left(\frac{V'}{C}\right)^2\frac{1}{R}$	Distance between Stations L	Friction Head.	Correction for Diff. in Vel. heads: P.C. Asmd Recvd	Correction for Diff. in Vel. heads	Computed difference in Elev. of water Surface.	Surface elevations at Stations found by computations.
	C F.S.	Sq. Ft.	Ft. per Sec.	Ft per Sec			in 10,000 Ft.	Ft.	Ft.	%	Ft.	Ft.	Ft. above Sea
XIX	153,000	70,900	2.15										567.00
				1.98	16.7	91	0.284	3,150	0.089	–	+.02	0.11	
XVIII	"	84,800	1.81										567.11
				1.52	15.1	77	.258	5,900	.152	–	+.027	.18	
XVII + XV C	"	124,400	1.23										567 29
XVII	99,000	96,700	1.02										567 29
				1.04	15.5	107	.060	5,050	.031	60	–.001	.03	
XVI + XVII C	"	93,200	1.06										567.32
XVI	58,000	59,100	0.98										567.32
				1.05	16.0	78	.113	6,150	.069	70	–.003	.07	
XV	"	52,100	1.11										567 39
				1.19	16.7	71	.202	9,900	.166	70	–.004	.16	
XIV	"	45,800	1.27										567.55
				1.40	15.7	76	.216	6,650	.143	70	–.008	.14	
XIII	"	37,900	1.53										567.69
				1.35	16.5	77	.187	9,300	.174	–	+.015	.20	
XII	"	49,200	1.18										567.89
				1.39	21.8	71	.176	9,300	.164	50	–.009	.16	
XI	"	36,250	1.60										568.08
				1.50	24.0	105	.085	8,750	.074	–	+.009	.08	
X	"	41,500	1.40										568.13
				1.43	23.6	104	.081	11,900	.096	50	–.001	.10	
IX	"	39,400	1.47										568.23
				1.41	19.5	114	.079	5,000	.040	–	+.015	.06	
VIII	"	42,700	1.36										568.29
VIII + VIII C	153,000	99,500	1.60										568.29
				1.80	15.9	110	.168	6,170	.104	60	–.013	.09	
VII	"	76,700	1.99										568.38
				2.66	20.4	110	.286	8,000	.228	60	–.066	.16	
VI	"	46,100	3.32										568.54
				4.23	21.7	104	.762	7,700	.586	50	–.119	.47	
V	"	29,800	5.14										569.01
				5.96	16.1	70	4.500	1,400	.630	50	–.150	.48	
IV	"	22,600	6.77										569.49
				6.29	13.3	97	3.160	1,000	.316	–	+.187	.50	
III	"	26,300	5.82										569.99
				4.71	13.1	98	1.770	3,500	.618	–	+.373	.99	
II	"	49,000	3.12										570.98
				2.69	13.9	53	1.850	1,600	.296	–	+.079	.38	
I	"	68,000	2.25										571.36

BACKWATER TABLE VI — AVERAGE DISCHARGE

Data from which elevations for backwater curves were computed by successive approximations — FOR TONAWANDA CHANNEL

Discharge from Lake Erie 209,000 C.F.S. — Chippawa Pool held at Elev. 571.5

Station	Discharge Q	Area of channel cross section A	Corresp. mean velocity at Station $V=\frac{Q}{A}$	Between Stations: Mean Velocity V'	Mean Hyd. Radius R	Value of C used	Slope of water surface due to friction $S=(\frac{V'}{C})^2\frac{1}{R}$	Distance between Stations L	Friction Head	Correction for Diff. in Vel. heads: P.C. Asmd Recvd	Correction: Ft.	Computed difference in Elev. of water surface	Surface elevations at stations found by computations
	C.F.S.	Sq. Ft.	Ft. per Sec.	Ft. per Sec.			In 10,000 Ft.	Ft.	Ft.	%	Ft.	Ft.	Ft. above Sea
XIX	209,000	93,450	2.24										571.50
				2.07	19.0	91	0.272	3,150	0.086	–	+.012	0.10	
XVIII	"	110,400	1.90										571.60
				1.60	19.6	77	.220	5,900	.130	–	+.030	.16	
XVII+XVC	"	160,600	1.30										571.76
XVII	135,000	124,500	1.08										571.76
				1.10	20.0	98	.064	5,050	.032	–	+.032	.04	
XVI+XVIIC	"	120,500	1.12										571.80
XVI	79,000	75,600	1.05										571.80
				1.12	20.4	76	.108	6,150	.067	70	-.002	.07	
XV	"	66,600	1.19										571.87
				1.28	21.1	71	.154	9,900	.153	70	-.005	.15	
XIV	"	57,500	1.37										572.02
				1.48	20.1	76	.189	6,650	.125	70	-.007	.12	
XIII	"	49,900	1.58										572.14
				1.45	20.9	77	.168	9,300	.156	–	+.013	.17	
XII	"	60,500	1.31										572.31
				1.58	26.2	75	.169	9,300	.156	50	-.013	.14	
XI	"	42,750	1.85										572.45
				1.68	29.3	118	.082	8,750	.072	–	+.018	.09	
X	"	52,250	1.51										572.54
				1.68	28.9	120	.068	11,900	.081	50	-.005	.08	
IX	"	46,720	1.69										572.62
				1.56	23.9	126	.064	5,000	.032	–	+.012	.05	
VIII	"	55,000	1.43										572.67
VIII+VIIIC	209,000	121,800	1.72										572.67
				1.93	20.3	106	.163	6,150	.101	60	-.015	.09	
VII	"	97,550	2.14										572.76
				3.00	24.8	103	.340	8,000	.263	60	-.095	.17	
VI	"	54,150	3.85										572.93
				4.76	26.2	104	.802	7,700	.618	50	-.135	.48	
V	"	36,800	5.68										573.41
				6.38	20.4	75	3.540	1,400	.495	50	-.133	.36	
IV	"	29,670	7.04										573.77
				6.52	17.6	98	2.510	1,000	.251	–	+.210	.46	
III	"	34,800	6.00										574.23
				4.60	17.4	100	1.220	3,500	.426	–	+.401	.83	
II	"	65,300	3.20										575.06
				2.82	18.0	55	1.460	1,600	.233	–	+.067	.30	
I	"	86,100	2.43										575.36

BACKWATER TABLE VII — MEDIUM LOW DISCHARGE

Data from which elevations for backwater curves were computed by successive approximations — FOR TONAWANDA CHANNEL

Discharge from Lake Erie 180,000 C.F.S. — Chippawa Pool held at Elev. 571.5

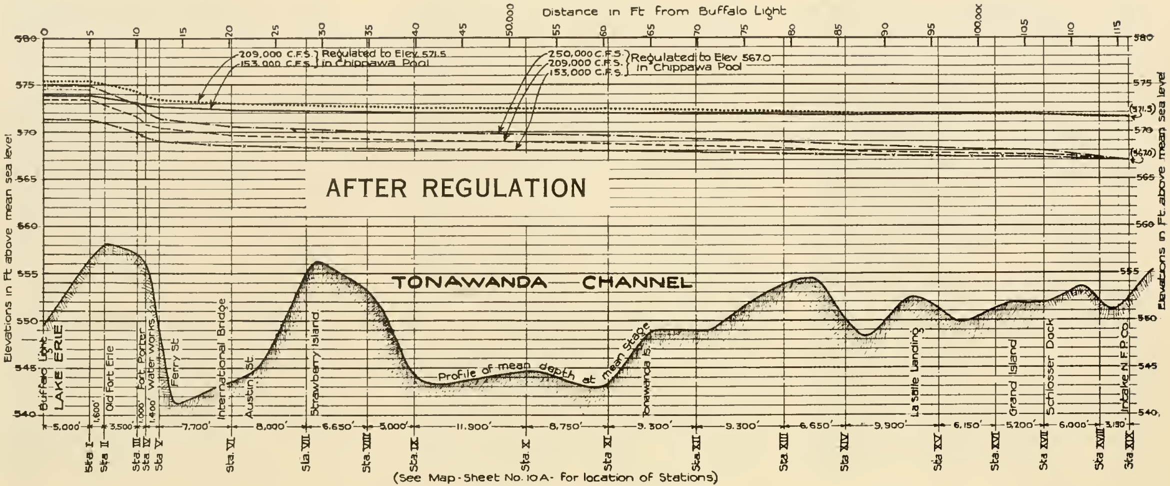
Station	Discharge Q	Area of channel cross section A	Corresp. mean velocity at Station $V=\frac{Q}{A}$	Between Stations: Mean Velocity V'	Mean Hyd. Radius R	Value of C used	Slope of water surface due to friction $S=(\frac{V'}{C})^2\frac{1}{R}$	Distance between Stations L	Friction Head	Correction for Diff. in Vel. heads: P.C. Asmd Recvd	Correction: Ft.	Computed difference in Elev. of water surface	Surface elevations at Stations found by computations
	C.F.S.	Sq. Ft.	Ft. per Sec.	Ft. per Sec.			In 10,000 Ft.	Ft.	Ft.	%	Ft.	Ft.	Ft. above Sea
XIX	180,000	93,450	1.93										571.50
				1.78	18.97	91	0.201	3,150	0.064	–	+.017	0.08	
XVIII	"	110,300	1.63										571.58
				1.38	19.60	77	.163	5,900	.095	–	+.022	.12	
XVII+XVC	"	160,200	1.12										571.70
XVII	116,500	124,100	.93										571.70
				.95	20.00	107	.040	5,050	.020	60	-.001	.02	
XVI+XVIIC	"	119,450	.98										571.72
XVI	68,500	75,250	.91										571.72
				.97	20.60	78	.075	6,150	.046	70	-.003	.04	
XV	"	66,350	1.03										571.76
				1.12	21.00	71	.118	9,900	.116	70	-.004	.11	
XIV	"	57,100	1.20										571.87
				1.29	20.00	76	.145	6,650	.095	70	-.005	.09	
XIII	"	49,400	1.39										571.96
				1.22	23.30	77	.120	9,300	.112	–	+.010	.12	
XII	"	60,000	1.14										572.08
				1.38	26.0	75	.131	9,300	.120	50	-.010	.11	
XI	"	42,330	1.62										572.19
				1.51	28.2	118	.058	8,750	.050	–	+.010	.06	
X	"	48,750	1.41										572.25
				1.44	27.7	120	.052	11,900	.062	50	-.002	.06	
IX	"	46,150	1.48										572.31
				1.38	23.6	126	.051	5,000	.025	–	+.009	.04	
VIII	"	54,050	1.27										572.35
VIII+VIIIC	180,000	119,900	1.50										572.35
				1.69	20.0	106	.127	6,170	.079	60	-.012	.07	
VII	"	96,000	1.88										572.42
				2.62	24.5	103	.264	8,000	.211	60	-.073	.14	
VI	"	53,500	3.37										572.56
				4.18	25.7	104	.627	7,700	.483	50	-.105	.38	
V	"	36,100	4.99										572.94
				5.64	19.9	75	2.840	1,400	.398	50	-.115	.28	
IV	"	28,600	6.29										573.22
				5.83	17.0	98	2.080	1,000	.208	–	+.168	.38	
III	"	33,600	5.36										573.60
				4.14	16.6	100	1.035	3,500	.362	–	+.316	.68	
II	"	61,750	2.92										574.28
				2.56	17.1	55	1.255	1,600	.203	–	+.058	.26	
I	"	82,500	2.18										574.54

BACKWATER TABLE VIII — LOW DISCHARGE

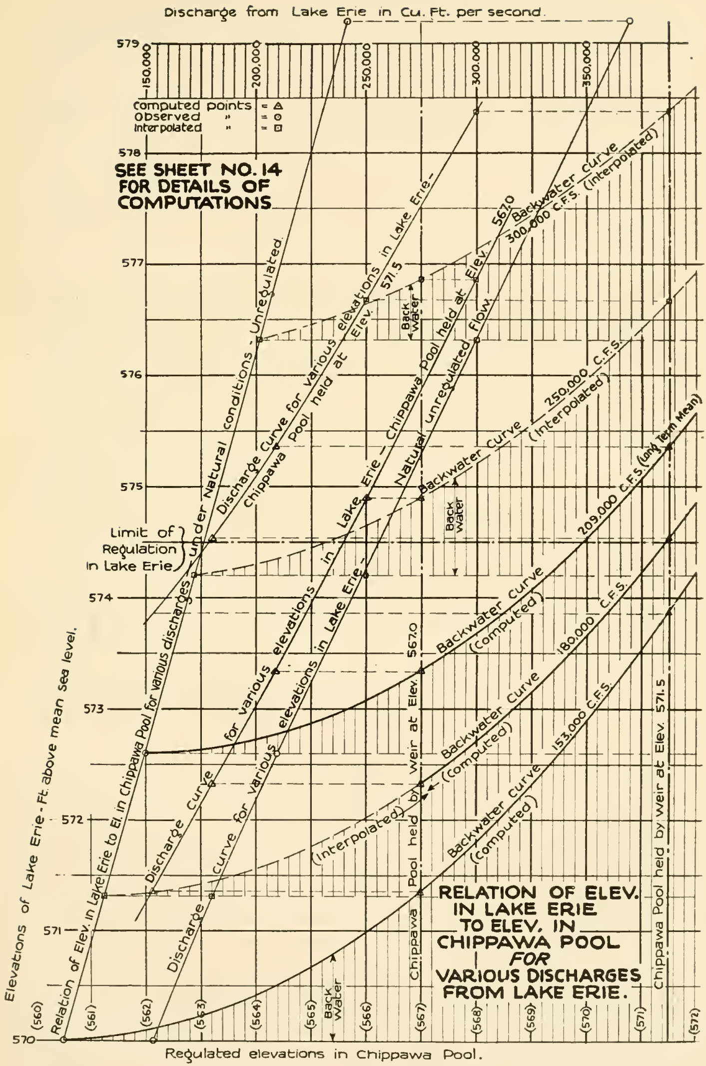
Data from which elevations for backwater curves were computed by successive approximations. — FOR TONAWANDA CHANNEL

Discharge from Lake Erie 153,000 C.F.S. — Chippawa Pool held at Elev. 571.5

Station	Discharge Q	Area of channel cross section A	Corresp. mean velocity at Station $V=\frac{Q}{A}$	Between Stations: Mean Velocity V'	Mean Hyd. Radius R	Value of C used	Slope of water surface due to friction $S=(\frac{V'}{C})^2\frac{1}{R}$	Distance between Stations L	Friction Head	Correction for Diff. in Vel. heads: P.C. Asmd Recvd	Correction: Ft.	Computed difference in Elev. of water surface	Surface elevations at Stations found by computations
	C.F.S.	Sq. Ft.	Ft. per Sec.	Ft. per Sec.			In 10,000 Ft.	Ft.	Ft.	%	Ft.	Ft.	Ft. above Sea
XIX	153,000	93,400	1.64										571.50
				1.52	18.9	91	0.146	3,150	0.046	–	+.012	0.06	
XVIII	"	110,100	1.39										571.56
				1.18	19.5	77	.120	5,900	.071	–	+.016	0.09	
XVII+XVC	"	159,700	0.96										571.65
XVII	99,000	120,900	0.80										571.65
				0.82	19.8	107	.029	5,050	.015	60	-.001	.02	
XVI+XVIIC	"	119,150	0.83										571.67
XVI	58,000	75,100	0.77										571.67
				0.82	20.3	78	.055	6,150	.034	70	-.002	.03	
XV	"	66,100	0.88										571.70
				0.95	20.9	71	.086	9,900	.084	70	-.003	.08	
XIV	"	56,900	1.02										571.78
				1.10	18.2	76	.106	6,650	.071	70	-.004	.07	
XIII	"	49,150	1.18										571.85
				1.08	20.7	77	.095	9,300	.088	–	+.007	.10	
XII	"	59,600	0.97										571.95
				1.17	25.8	75	.096	9,300	.089	50	-.007	.08	
XI	"	42,100	1.38										572.03
				1.29	28.0	118	.043	8,750	.037	–	+.007	.04	
X	"	48,400	1.20										572.07
				1.23	27.5	120	.041	11,900	.049	50	-.001	.05	
IX	"	45,900	1.26										572.12
				1.17	23.4	126	.037	5,000	.019	–	+.007	.03	
VIII	"	53,500	1.08										572.15
VIII+VIIIC	153,000	118,900	1.29										572.15
				1.45	19.8	106	.094	6,170	.058	60	-.009	.05	
VII	"	95,100	1.61										572.20
				2.25	24.3	103	.195	8,000	.156	60	-.053	.11	
VI	"	53,100	2.88										572.31
				3.59	25.4	104	.470	7,700	.362	50	-.079	.29	
V	"	35,600	4.30										572.60
				4.86	19.6	75	2.150	1,400	.302	50	-.089	.21	
IV	"	28,200	5.42										572.81
				5.06	16.6	98	1.610	1,000	.161	–	+.123	.29	
III	"	32,600	4.70										573.10
				3.63	16.0	100	.825	3,500	.288	–	+.241	.53	
II	"	59,400	2.57										573.63
				2.25	16.4	55	1.020	1,600	.164	–	+.045	.21	
I	"	79,400	1.93										573.84



PROFILE OF WATER SURFACE IN NIAGARA RIVER FOR VARIOUS STAGES AFTER REGULATION AS DETERMINED BY BACKWATER COMPUTATIONS



Discharge from Lake Erie in Cu. Ft. per second.
150,000
200,000
250,000
300,000
350,000
Computed points = △
Observed " = ○
Interpolated " = ▫
SEE SHEET NO. 14 FOR DETAILS OF COMPUTATIONS
579
578
577
576
575
574
573
572
571
570
Limit of Regulation in Lake Erie
Under Natural conditions - Unregulated.
Discharge Curve for various elevations in Lake Erie - Chippawa Pool held at Elev. 571.5
Lake Erie - Chippawa Pool held at Elev. 567.0
Natural unregulated flow.
Backwater curve 300,000 C.F.S. (Interpolated)
Backwater curve 250,000 C.F.S. (Interpolated)
Backwater curve 209,000 C.F.S. (Long Term Mean) (Computed)
Backwater Curve 180,000 C.F.S. (Computed)
Backwater Curve 153,000 C.F.S. (Computed)
(Interpolated)
Back Water
Relation of Elev. in Lake Erie to El. in Chippawa Pool for various discharges
Discharge Curve for various elevations in Lake Erie
Discharge curve for various elevations in Lake Erie
Chippawa Pool held by weir at Elev. 567.0
Chippawa Pool held by weir at Elev. 571.5
RELATION OF ELEV. IN LAKE ERIE TO ELEV. IN CHIPPAWA POOL FOR VARIOUS DISCHARGES FROM LAKE ERIE.
Elevations of Lake Erie - Ft. above mean sea level.
(560)
(561)
(562)
(563)
(564)
(565)
(566)
(567)
(568)
(569)
(570)
(571)
(572)
Regulated elevations in Chippawa Pool.

FLOWAGE DAMAGE ABOVE CHIPPAWA POOL

Attention also has been given to the possibilities of flowage damage along both the Canadian and the American shores of the Niagara River.

On the Canadian shore, the land is owned by the Canadian Government nearly all the way from Chippawa Pool to the head of the Niagara River and held as a public reservation. At a short distance from the shore there is a broad and excellent highway, and for much of the distance this highway and the shores appear to be safely above the proposed increase of water level. At all other points this highway apparently can be raised to the small extent necessary at a cost relatively small in proportion to the gains.

On the American shore, little if any damage would be caused by raising Chippawa Pool five feet, but for substantially greater increase in height, a low dike would be required along much of the shoreline nearly all of the way from the power house intakes to about a mile upstream from Tonawanda. A reconnaissance along the shores made by one of the members of this committee indicates no substantial difficulty in the construction of such a dike. It could be made a valuable asset to the whole region by placing upon it a broad highway. Much of this embankment and highway could be built on property along the shore owned by the U. S. Government, or by the State of New York, or within their riparian rights.

At Tonawanda the course of this dike and highway naturally would enclose the harbor and the new Erie Canal. (The old Erie Canal is now being filled up.)

In the immediate vicinity of Tonawanda, a new lock, presenting at most ten feet drop, would need be constructed for entrance to the Erie Canal.

The general level of the land adjacent to the river in the vicinity of Niagara Falls is at about El. 574 0 rising to El. 580.0 and in spots to El 600.0 feet above sea level, **which is from two to three feet higher than the maximum height proposed in the Chippawa Pool,** but at some points, particularly near Cuyuga Island, there would be some flowage, except for the dike. A broad high dike all along, surmounted by a highway and with ship landings on the outer side, may be useful for many purposes.

For providing ample drainage for the territory inshore from the dike, it is proposed to construct a canal about 70 feet wide by two or three feet deep below the present level of the Niagara River, with banks high enough to take the flood flow of Cayuga Creek and Gill Creek. The water in this canal would be kept fresh and clean by a slow current taken in from the river. This would discharge either down the parkway owned by the city of Niagara Falls along Gill Creek, or could pass in a tunnel beneath the power canals in a siphon rising at a point immediately down-stream from the east end of the regulation works so that none of this water would be lost to the falls.

Grand Island seems to present sufficient area for industrial works, adjacent to the great freight terminals recently planned, and by using future electrical power from Niagara, thus would relieve the demands upon the other shores.

It is presumed that wharves and docks would be provided for, extending into the river upon filled ground from the water side of the proposed embankment and highway, and that inshore from the highway and opposite to these wharves all necessary space could be found for industrial sites, and that these could have access to their wharves with least interference to future traffic along the highway, by means of overhead bridges and elevated railway crossings, from factory site to wharf.

This highway should be of ample width to provide a pleasure drive along the water side as well as an artery of rapid automobile transit between Buffalo and Niagara Falls.

There has been neither time nor opportunity for the writer to work out detailed estimates for these dikes and highways upstream from the Chippawa Pool, but it appears plain that the several benefits, conferred by the proposed structure and the rise in water level from the Chippawa Pool, above Buffalo Harbor would abundantly compensate for all of the necessary expenditure upon these developments made in connection with harbor extension and future deep waterways to the sea, and which are not a necessary part of the project for regulating the elevation and discharge of the lakes.

ADVANTAGES OF WORKS 20 MILES DOWNSTREAM FROM LAKE ERIE

These benefits, already mentioned on pages 237 and 238, comprise those named below:

(a) The large increased carrying capacity of the Chippawa-Queenston Canal leading from the Chippawa Pool to the Canadian Hydro plant. This canal was extremely costly, and comprises in large part, a deep open cut in solid rock. The additional carrying capacity would suffice for a very large increase in the turbine installation at Queenston, with relatively little or no cost for canal construction.

(b) The American-Niagara Power plants would be benefited by increased head and increased carrying capacity of canal, but not to so noteworthy a degree as the Canadian plants. A relatively larger expenditure would be required to give these American plants the full benefit of increased head.

(c) The facilities for ice removal and for avoiding interruption of the power plants by anchor ice and frazil ice would be greatly improved by the new channels leading to the American Fall and by the facilities for rapid discharge presented in dropping several of the gates and creating a swift current out from the pool.

(d) **The increase in harbor facilities at the outlet of Lake Erie by thus extending the present greatly restricted and sometimes dangerous limits of Buffalo Harbor would seem to be worth far more than all needed expenditure on dikes and a new lock at Tonawanda for entrance to the Erie Canal.**

(e) **The present harbor of Buffalo is restricted in area of docks and in anchorage facilities and there is reported to be much danger involved in mooring boats against heavy wind within its restricted area.**

(f) The transcontinental railroad systems are understood to be already purchasing large tracts on

Grand Island for future terminals and transportation yards, which would be adjacent to the proposed new harbor facilities.

It is obvious, from inspecting the navigation chart, that if works of the kind now suggested are found feasible by which the water level throughout all this region can be largely raised, **a remarkably advantageous condition of new harbor frontage would be created all along the easterly bank of the Niagara River throughout a distance of more than 20 miles** between Buffalo, Tonawanda and Niagara Falls and around the shores of Grand Island.

Looking to the future possibilities of increased transportation **other than ore and coal** via the Great Lakes and the probabilities of a deep waterway to the sea within the next 20 years, it seems important to keep these possibilities all actively in the foreground, while making any designs for the improvement of lake levels.

LOCKS AND REGULATING WORKS IN THE ST. CLAIR RIVER

Location

The works proposed are shown in 18 sheets of drawings, each 24 in. x 36 in., copies of most of which are attached hereto.

Sheet No. 1 of the St. Clair Series of which a copy on reduced scale is given on page 336 A, shows the location selected provisionally for purposes of designs and estimates, which is about 13½ miles downstream from Lake Huron, near St. Clair City.

This site was chosen because of the river here presenting sufficient width so that cofferdams and structures in process of building need occupy only one half of the river, while the other half was left clear, presenting ample space for passage of shipping.

Obviously, **the farther down toward Lake Erie that these gates and sluices can be placed, the better it will be for lessening excavation in the navigation channels** between the two Great Lakes, Huron and Erie; but in the absence of precise surveys it was not deemed prudent to make preliminary designs for a point farther downstream than that selected, where the high banks on both sides the St. Clair River came practically to an end.

The slight back-water which these regulation works may throw back on the relatively steep slope and swift current in the gorge at the outlet of Lake Huron, obviously, will be beneficial so far as it goes; because the present current of 5 miles per hour at this outlet is inconveniently swift for a narrow pass-way 2 or 3 miles long that is not straight.

After the proposed regulation works have been built, this narrow gorge can be cut out to a greater width to give slower current, with great advantage and without danger of lowering Lakes Huron and Michigan.

Downstream from this point shown, which is 13½ miles down from Lake Huron, for the entire length of the St. Clair River perhaps the banks are high enough to permit locating the regulation works farther downstream; possibly at the outlet of Lake St. Clair, or possibly still nearer to the city of Detroit, where these works would provide a convenient foundation upon which to build an elevated steel-truss highway bridge connecting the United States with Canada.

Possibly, a careful survey would show that the increased elevation of water to be caused by gates at these downstream locations would not rise higher than has been caused theretofore by ice-gorges. The tendency to form ice gorges probably will be lessened by the presence of the regulating works. Obviously, although there were complete stoppage, it could never rise higher than the level of Lake Huron.

The present fall in 58 miles of channel from the proposed regulated high water of Lake Huron at El. 583.50 above mean sea level, to the ordinary water level of El. 575.0 at the outlet of Lake St. Clair, is 8.5 ft.

In the winter season, if, in order to gain storage or increase the level of Lake Huron, with the utmost rapidity and with Lake Huron at 583.5, all of these sluice-gates should be closed to the utmost and only the Fairway open, the discharge would be 137,000 cu. ft. sec., or 75 per cent of the normal discharge, and the fall from Lake Huron to the gates, 0.9 feet to elevation 582.6, giving an extreme drop in water surface from upper to lower sides of gates of 5.82 feet, as will appear from the hydraulic diagrams presented later in this report.

On the other hand, with gates all wide open, the drop from upper to lower side of the gates or through the locks, will be only about 0.4 ft.

Ordinarily, the fall at the locks will be between 3 and 4 feet.

The economy of combining a new highway bridge with the regulating works has some weight in considering which location is best. Obviously, a highway bridge near Windmill Point, only seven or eight miles upstream from Twelfth Street in Detroit, would be more generally useful than if located between St. Clair City, Michigan, and the villages of Moore and Courtright in Canada and possibly they can be located still nearer to the center of Detroit.

Also, by locating the works at Windmill Point the channel through Lake St. Clair up past Marine City, would become deepened to the extent of from two to four feet in the navigation season, without expense of dredging, and the large cost of this dredging should be offset against flowage damage.

If these proposed regulation works are located near Windmill Point is estimated that the water in Lake St. Clair would never rise more than a foot and a half higher than that recorded on the charts for the high water of 1838. A reconnaissance should be made in order to learn if the saving in cost of dredging will not offset the probable cost of obtaining the necessary flowage rights for this location, so advantageous to Detroit and Windsor.

From the data now in hand, the location 13½ miles downstream from Lake Huron appears to be certainly practicable, and the designs and estimates of costs, therefore, are based upon this location, which is feasible beyond all reasonable doubt.

Possible locations farther downstream should, however, be investigated.

DESIGN PROPOSED FOR ST. CLAIR REGULATION WORKS

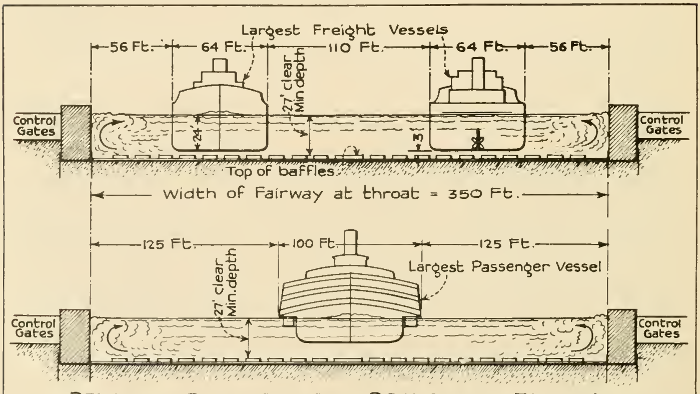
The general outline of the proposed layout of future locks, gates, sluices, and fairway, is shown on St. Clair Sheet No. 2, page 336 B, as the final result of much preliminary sketching and re-arranging.

Much care was taken to select a site presenting a long view in both directions, for pilots and lock keepers watching the approach of boats in opposite directions.

This design is presented with confidence that it will meet all needs of navigation for more than a half century of further developments in navigation and water power, and will permit of all necessary control of storage and elevation in Lakes Michigan and Huron at the highest practicable levels.

This design permits flexibility in operation such that the controlled elevations of lake surface may be varied a foot or more up or down, or within all future possibilities for meeting new conditions. The locks and channels provide for ships of 25 ft. draft and 30 ft. draft and of as great width and length as are ever likely to enter the lakes.

Attention is first called to the open "Fairway" located one-half on each side of the International Boundary, and shown as presenting a minimum total width of 350 feet, through which all down-bound vessels can pass without detention, however great the difference in elevation from above to below. The great majority of up-bound boats also can pass without lockage, because of the care taken in designing this structure so as to both retard the velocity and to throw the surface current away from the sides and towards the center, by an arrangement of inclined baffles built of concrete along the floor of the structure.



RELATIVE DIMENSIONS OF BOATS AND FAIRWAY.

A width of only 300 feet or possibly 250 feet would be strongly preferable for storage control, and in the opinion of the writer would be ample for all practical purposes of navigation; but as a concession to possible fears, the extra 50 feet, or 100 feet, has been added in the present drawings, although this is to the disadvantage of power development.

Much care has been taken in shaping the approaches and in placing the exit and entrance of the fairway, in relation to the gates, so as to avoid eddys and cross currents that might make steering difficult. One model on a small scale of 1 to 200 has been experimented with for learning more definitely about action of the baffles on the bottom. (These experiments proved, as has been suspected, that only half the number of baffles shown on the drawing are necessary.) More extensive experiments with larger scale models are desirable before proceeding with construction.

The difference of level between the two ends of the fairway will be so small much of the time, that the maximum velocity in the throat can be easily overcome by most of the up-bound boats. In general, ore boats going upstream, although carrying coal, are more lightly loaded than those coming downstream, and many go upstream unloaded.

When the difference of level between the two ends of the fairway is greatest, the maximum velocity in the throat will be only about 7.3 miles per hour, or well within the capacity of most boats although fully loaded. Moreover, this high velocity exists over a distance only about twice the length of one of the larger boats, and the momentum of the boat at ordinary speed would largely overcome the extra resistance over this short space, with no great reduction of the speed of the boat relative to the shore. A long straight-away approach is provided for in the design.

The flare, or excess width, given at the two ends has been carefully proportioned so as to distribute the fall of water surface at the upstream end uniformly for a long distance, and is designed to present low current velocities at entrance and exit and thus avoid eddies which might render steering difficult. The writer believes that possibly, after experience with the trend of the currents, an upbound and a downbound boat each of the largest size could safely pass midway in the short throat, which is only 1,000 feet long, but probably it will be thought safer to reserve the fairway for down-bound boats.

Until pilots become familiar with the currents through the fairway, any who are in doubt can put their ships through the locks, both up and down, just as they do now at Sault Ste. Marie; but, can do this in much less time because of the lessened lift and the improved methods for filling and emptying the lock within the required limits at a rapid rate with a minimum of internal surging and eddying and internal commotion. The entire operation of lockage with this small lift of from 2 ft. to 4 ft. need not take over 15 minutes; but, including delays of entering and loss of headway, the delay due to lockage probably will be half an hour.

The time ordinarily taken for a round trip from Duluth to Cleveland, Conneaut or Buffalo averages about 11 or 12 days, or say 276 hours. So that **a half hour delay for lockage on the up trip is only one-fifth of one per cent of the time of a round trip,** which would be far more than offset by the gains in speed and depth of loading in the deeper channels which these locks will provide.

One-half of one per cent of a ten-day round trip is 1.2 hours.

The locks are designed as long and as wide as the most recent locks at the "Soo." The lock on the American side is made 100 feet in width, in order to accommodate the largest passenger boats. The clear length of 1,350 feet for all of the proposed locks, which is the same as the length of the latest locks at Sault St. Marie, makes fleet lockage practicable for two of the largest boats simultaneously.

Because of the large proportion of all the traffic which will pass through the fairway and not use the locks, the writer believes it is not probable that any additional locks will be needed within the next fifty years beyond the two shown, one on the Canadian and the other on the American side; but provision is made in the layout for building one, or even two additional locks on each side, conveniently and without obstructing the operation of the existing works should an additional lock ever become necessary.

The layout and the hydraulics of the fairway are shown on Sheet No. 4, page 336 c.

Experiments that have recently been made on a small model at the Massachusetts Institute of Technology indicate that half the number of baffle piers shown on this drawing will be sufficient to produce the desired results in retardation of current and in causing a sort of spiral circulation of water in each half of the fairway, with bottom currents tending outward and **surface currents tending slightly inward, which will tend to prevent a boat, or other floating substance, from coming in contact with the side walls.**

It will be noted that the fairway is to be provided with a reinforced concrete floor, nowhere less than four inches in thickness, in order to prevent all possibility of scouring of bed and undermining of side walls. The clear depth above the top of the baffles is made 27 feet so that if a boat draws 25 ft. when fully loaded, the pumping out of water by the propeller from beneath its stern will not cause it to come in contact with the tops of these piers; nevertheless, the tops of all the piers are made broad and flat so that contact would not cause injury.

The hydraulic diagram on page 327 gives discharge for depths of both 27 ft. and 32 ft. but only for the width of 350 ft. Allowance for reduced width can be readily made by proportion.

30 feet future depth of draft could easily be provided for in the beginning, by adding 5 feet to the depth shown on the drawings, but this should be compensated for by narrowing from 350 feet to 275 feet, **in order to retain sufficient control of the discharge for regulating purposes.**

The hydraulics of the St. Clair River in its natural state present complicated problems, because of the varying fall between Lakes Huron and Erie and also because of the variations in elevation of each Lake; so that to work out the effect of the proposed structures under all of these variable conditions presents further complications; but fortunately they are not beyond safe and certain solution within margins of error so small that there can be no serious doubt that under all conditions liable to be presented, the proposed works can be made to function as desired.

The results of many computations have been condensed and reproduced in diagrams C, D, and E, given on pages 323–325, from which one versed in hydraulic science can readily obtain an answer to a great variety of questions: for example, as to what the fall from the upstream side to the down-stream side of the regulating works will be under any condition of discharge, and for any heights in Lakes Huron and Erie.

It will be noted from the table on page 329, that the velocity through the fairway is smallest when the discharge through the St. Clair River is the greatest, because much of the water then passes through the gates instead of through the fairway; and that during a considerable part of the navigation season the velocity in the fairway will be only from three to four miles per hour, or less than that now found in the head of the St. Clair River.

During the navigation season and with the average flow through the St. Clair River recorded for the past twenty-five years of 175,000 cubic feet per second, and with Lake Huron and Lake Erie at their proposed regulated mean stages, the drop at the regulating works, or in other words, the height of the lockage, will be only 3.2 ft. or only one sixth part of the height of lockage at the "Soo." Meanwhile 107,000 cu. ft. sec. or about 60 per cent of the total discharge of the river will pass through the fairway and the remaining 68,000 cu. ft. sec. through the sluices.

The extreme difference in height at the locks will occur in the non-navigation season, while gates are closed to the maximum amount, as for the purpose of accumulating storage in Lakes Michigan and Huron, and may then at times possibly be as much as 5.8 ft.

With all gates closed, **the discharge under this extreme head,** through the open fairway having a depth of 27 feet and a width of 350 feet in the narrowest portion, **would be about 136,000 cubic feet per second.** In other words, the discharge under these conditions would be about 70 per cent. of the mean discharge of the St. Clair River for the past twenty-five years; which with the aid of Lake Erie is more than sufficient to supply Niagara River with water enough for power and scenery during the winter season.

The lowest discharge to which it will be possible to regulate the flow in the non-navigation season by closing all gates when Lake Huron and Lake Erie are **at their mean stages,** will be 121,000 second feet, which is about 66 per cent of the average flow of the St. Clair River for the past twenty-five years, and is not so great a reduction as sometimes has been caused by ice.

Thus it is seen that with all gates closed the open fairway will permit a large discharge of the St. Clair River.

In the extremely severe winter of 1900–1, the ice-blockade reduced the discharge of the St. Clair River to only about 105,000 c.f.s. for nearly all of the month of February.

The gates and sluices in connection with the open fairway, thus, only place under human control, whenever desirable, the restriction and accumulation of storage in winter for use in summer, which nature now exercises on rare and uncertain occasions.

All the interests of the public taken as a whole, would be better served with a smaller width of fairway, which would permit holding back a larger proportion of the flow for storage during the winter months, and **in the opinion of the designer a 300 ft. width would be more than ample for the needs of navigation** in this extremely short passage with long, straight approach and the carefully arranged location of ends so as to avoid cross currents. 300 feet is the width for several miles through the Culebra Cut of the Panama Canal which has ragged shores but no current. With this extremely short length through the fairway, the long straight approach, the off-shore tendency of the surface currents within the fairway, caused by the inclination of the baffles, and with its smooth side walls, it is plain that the width could safely be made smaller than at Panama, notwithstanding the current in the St. Clair. **250 feet probably would be ample.** The designer has for present purposes resolved all doubt in favor of presenting a maximum width for navigation, but **recommends that a smaller width be considered.**

HYDRAULICS OF ST. CLAIR REGULATING WORKS AND FAIRWAY

The important hydraulic problems are: having given

(1) The profile of the St. Clair and Detroit Rivers as determined by the precise levels and surveys for the Board of Engineers for Deep Waterways, and presented in their report of 1900, supplemented by many observations of the total drop between Lakes Huron, St. Clair and Erie, and

(2) Many profiles of surface within the 5 miles of the St. Clair River immediately downstream from Lake Huron.

(3) Distances and depths by the recent navigation charts of the U. S. Lake Survey.

(4) Further detailed surveys of cross-sections near the head of the St. Clair River, made in course of the current meter measurements of discharge, 1888 to 1903. (See map on page 399.)

(5) Discharge formulas and diagrams giving the rate of flow in cubic feet per second for various elevations of Lake Huron, Lake St. Clair and Lake Erie.

(6) Given sluiceways of shape and area shown in the accompanying designs for Regulating Works and Fairway in the St. Clair River.

It is required to compute

(7) The new profiles of river surface.

(8) The amount of drop or lift at the sluice gates and navigation locks for various conditions of lake levels and discharge.

(9) The velocity of current through the fairway for various conditions of discharge.

(10) The quantity discharged by the open Fairway for various conditions of drop of river surface at the Regulation Works.

The hydraulic conditions at the outlet of Lake Huron are less permanent than at the outlet of Lake Erie and there are complications in the varying relations of heights in the three lakes — Huron, St. Clair and Erie — which make the conditions much more complicated than those under which the coefficients of channel resistance and new profiles caused by regulation works were deduced for the upper Niagara River in the preceding pages, 297 to 310. Moreover, the precision of the formulas that have been deduced for the discharge of Huron are less satisfactory than those for Lake Erie, because of the more complicated conditions mentioned above.

First, as to formulas or diagrams of discharge, it is obvious that while elevation in Lake Huron exercises the Chief Control, this discharge also is affected by the height in Lakes St. Clair and Lake Erie, (altho to a much smaller extent per foot in height of lake,) because of the elevation of these downstream lakes being so high above what we may call the submerged weir over which the water passes near Lake St. Clair.

One diagram for discharge in terms only of elevation of Lake Huron has been presented on page 212, another in terms of heights in both Huron and St. Clair is presented on page 32 , and this is followed by a third diagram for determining the Huron discharge in terms of both Huron and Erie.

The next step is the computation of the coefficient of frictional resistance of the St. Clair and Detroit River channels in the Chezy formula, from data already described above, by methods similar to those used for the similar computation for the Niagara-Tonawanda Channel on page 303. The various important data steps and results in this computation are condensed into the table on the next page.

Data were not available regarding the cross-sections and water elevations at frequent intervals, all along this 80 mile water course, therefore the values for coefficient were computed as a whole instead of step by step as for the Niagara River. This gives a degree of precision ample for present purposes.

HYDRAULIC CHARACTERISTICS OF ST. CLAIR AND DETROIT RIVERS

The total channel length of 64.7 miles, not including the distance across Lake St. Clair (18.08 miles) from St. Clair Flats to windmill Point, is subdivided by the location shown for the regulating works into two sections, which must be considered separately.

(1) From Lake Huron to site of Proposed Regulating Works, 13.6 miles (71,720 feet) downstream from Fort Gratiot Light House.

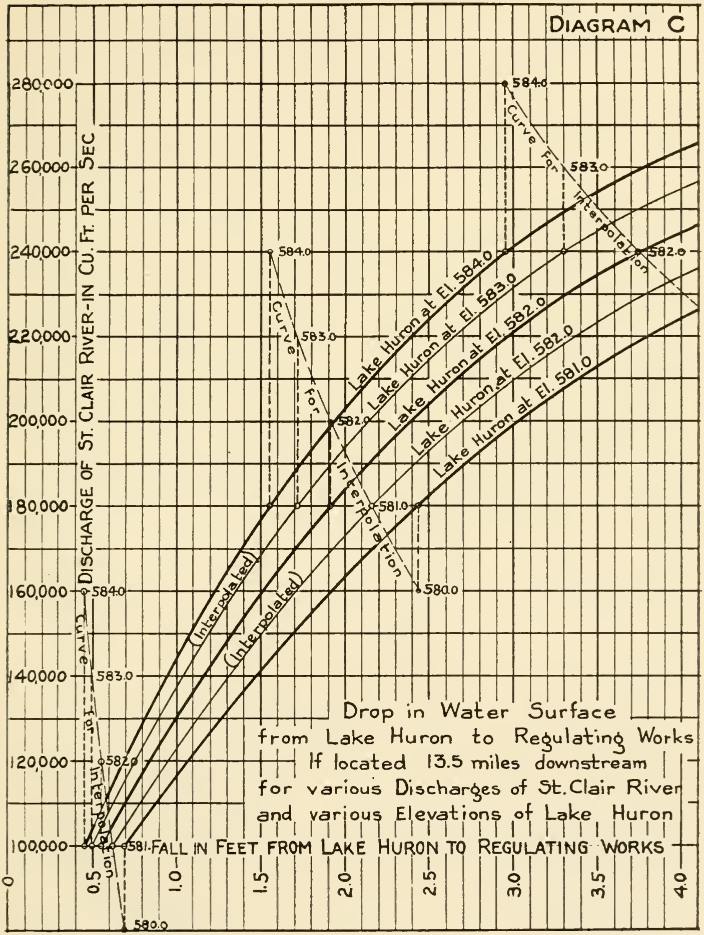
(2) From site of Proposed Regulating Works to Lake Erie at Gibraltar, a distance of 51.12 miles (269,910 feet).

The computations below are based on the profiles of river surface made under the direction of the Board on Deep Waterways, October 10 to 15, 1898, and June 26, July 1, 1899.

	Elev. of Lake Huron at Harbor Beach	Elev. of River surface at Site of Proposed Reg. Works	Elev. of Lake Erie at Gibraltar	Quantity of Flow	Total Drop in Surface	Length of Reach	Aver. Hydraulic Radius	Aver. Width of Channel	Aver. Area of Channel	Aver. Velocity of Flow	Head Required for Velocity	Head Used to overcome friction	Friction Slope "S"	Computed Coefficient "C" for Chezy Formula
	Feet	Feet	Feet	100 c.f.s.	Feet	100 Feet		Feet	100 sq. ft.	ft. per sec.	Feet	Feet	ft. per 10,000	
For reach of River from Lake Huron to site of Proposed Regulation Works	580.21	577.41	——	1900	2.80	717	26.9	2350	633	3.00	0.14	2.66	.371	96
	580.86	577.95	——	2045	2.91	717	27.5	2350	646	3.16	0.15	2.75	.385	97
For reach of River from site of Regulation Works to Lake Erie	——	577.41	571.99	1900	5.42	2699	24.2	4165	1008	1.89	0.16*	5.26	.195	87
	——	577.95	572.65	2045	5.30	2699	24.8	4165	1033	1.98	0.18*	5.12	.189	91

*It is assumed that the velocity head is lost at entrance to Lake St. Clair and must be developed again at outlet of Lake.

Having the values of this channel coefficient "C", we are able to next compute the drop in water surface between Lake Huron and the proposed site of regulating works and thence to Lake Erie, and to prepare Diagrams C and D, showing this drop for various rates of discharge under natural conditions.



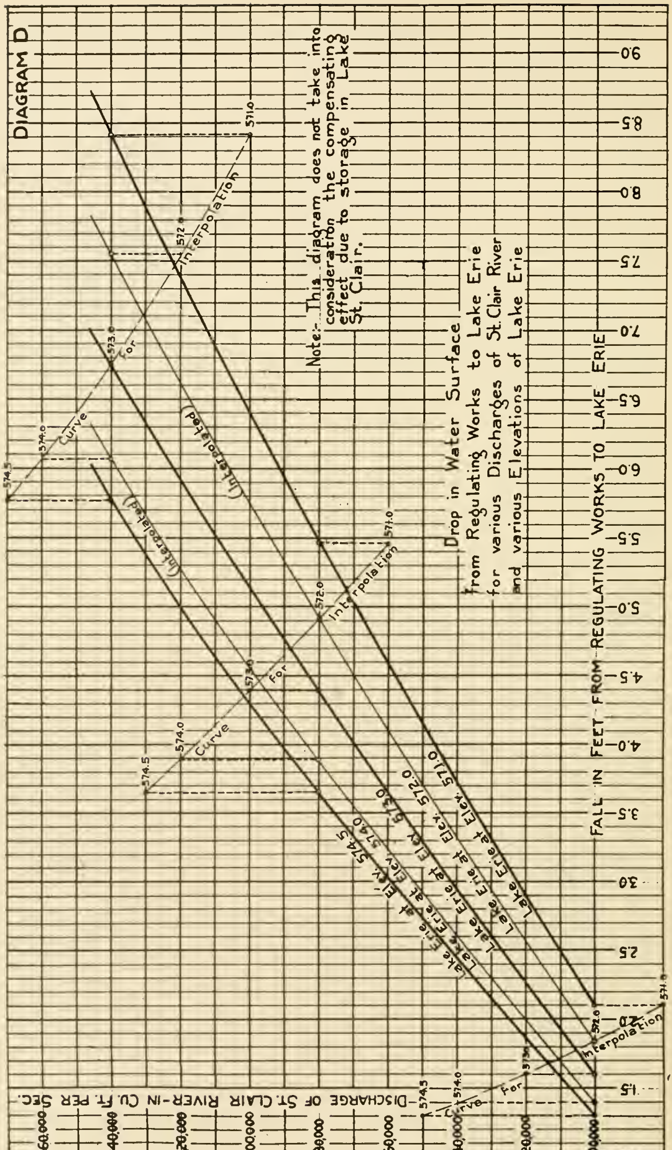


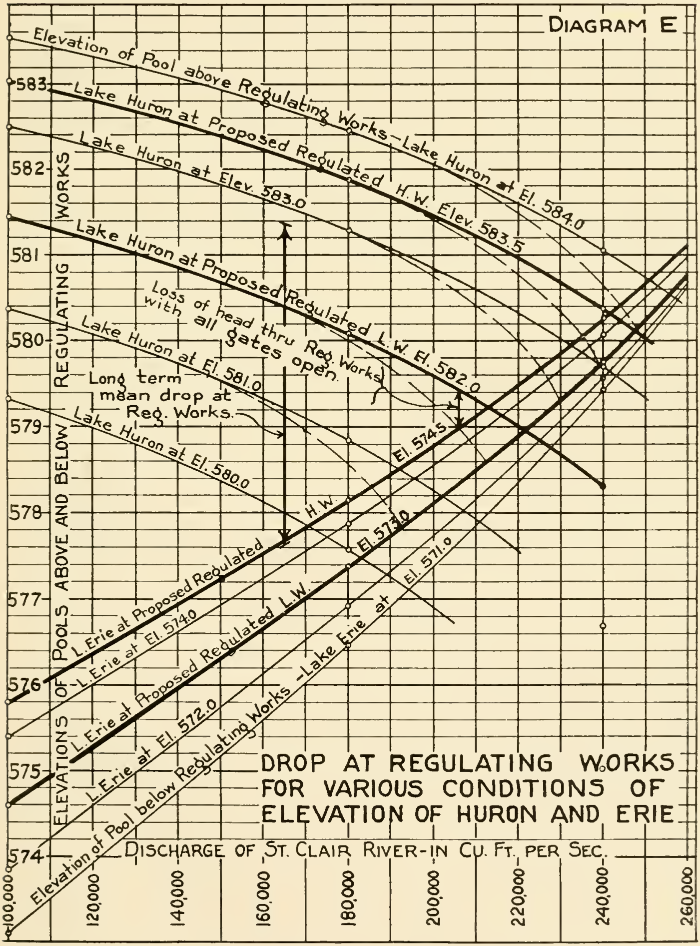
DIAGRAM D
Note:- This diagram does not take into consideration the compensating effect due to storage in Lake St. Clair.
Drop in Water Surface from Regulating Works to Lake Erie for various Discharges of St. Clair River and various Elevations of Lake Erie
FALL IN FEET FROM REGULATING WORKS TO LAKE ERIE
DISCHARGE OF ST. CLAIR RIVER-IN CU. FT. PER SEC.
Lake Erie at Elev. 574.5
Lake Erie at Elev. 574.0
Lake Erie at Elev. 573.0
Lake Erie at Elev. 572.0
Lake Erie at Elev. 571.0
(Interpolated)
Curve For Interpolation
260,000
240,000
220,000
200,000
180,000
160,000
140,000
120,000
100,000
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
9.0

The next step is to compute Diagram E showing the drop which will exist at the regulating works for various elevations of Lake Huron and of Lake Erie, when gates are closed so as to restrict the discharge to various stated amounts. For this purpose it is necessary to combine two diagrams into one because the result is comprised in the distance between two variables — (1) height at upstream side, (2) height at downstream side — each of which depends upon three independent variables.

(1) The regulated elevation of Lake Huron.

(2) The regulated elevation of Lake Erie.

(3) The quantity to be discharged through the St. Clair River.



Obviously, having the value C, determined from this channel, and the general dimensions of the channel it is a simple matter to compute and lay down the curves showing the elevation of water surface at the downstream side of works corresponding to any value for each of the two variables, (1) the elevation in Lake Erie, (2) the quantity to be discharged.

The computation of profile began at Lake Erie and proceeded step by step upstream.

For the drop between Huron and the works, a similar method is followed starting from Huron and working step by step downstream. This was done for enough points to determine the main curves and other points and curves were then interpolated.

Having the two sets of curves, the method of finding the drop at the regulating works—corresponding to a given discharge as controlled by the sluice gate-weirs—the procedure is to draw a vertical line on diagram E, corresponding to this stated quantity, and then spot its intersection on the curve for the stated regulated height in Erie and also its intersection with the stated regulated height in Huron, and by reading these on the scale at the left of diagram and subtracting; or by measuring directly with dividers or scale, for the required quantity, the drop through the gates or the lift through the locks is readily obtained. It is from this diagram E that the figures for drop or lift, given in table on page 329, were obtained.

The computation of discharge through the fairway for any given combination of heights on upstream and downstream sides is next in order. This is a relatively simple hydraulic problem of discharge through a flume of given size and shape under a given head for producing velocity, but the result depends largely upon the coefficient of roughness of the channel bed.

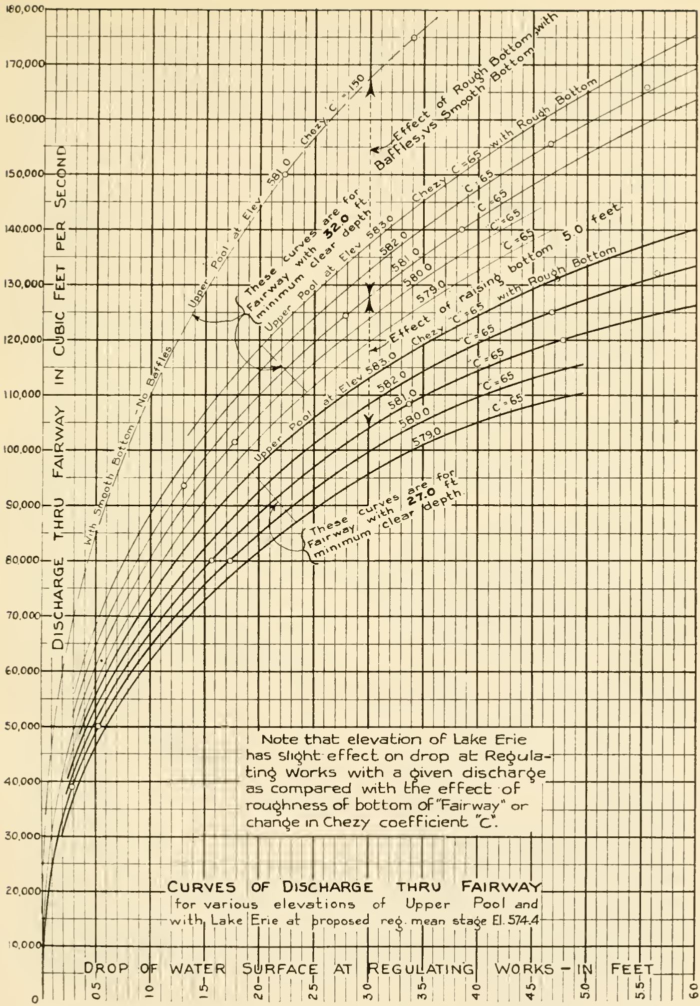
For the purpose of retarding the velocity of current to the greatest possible extent, baffle piers are built into the bottom, having flat tops, safely below the level of the deepest boat and inclined from center outward so as to induce a spiral current outward along the bottom, upward at the sides, and inward at the top.

The great difference between the quantity discharged with corresponding difference in strength of current with this rough bottom as compared with smooth bottom is shown by the two curves, for same elevation of 581.0 in the upper pool.

The drop through the fairway, or through the locks, will ordinarily be about 3.0 feet during the navigation season.

The drop will be at maximum in winter when gates are closed and storage is being accumulated.

When discharge through the river is at its maximum, sluice gates will be wide open and the drop through locks and velocity of current through fairway will be the least.



DISCHARGE THRU FAIRWAY IN CUBIC FEET PER SECOND
DROP OF WATER SURFACE AT REGULATING WORKS – IN FEET
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
90,000
100,000
110,000
120,000
130,000
140,000
150,000
160,000
170,000
180,000
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
Effect of Rough Bottom with Baffles, vs Smooth Bottom
Chezy C = 150
Upper Pool at Elev 581.0
With Smooth Bottom – No Baffles
Chezy C = 65 with Rough Bottom
These curves are for Fairway with 32.0 ft. minimum clear depth
Upper Pool at Elev 583.0
582.0
581.0
580.0
579.0
Effect of raising bottom 5.0 feet
Chezy C = 65 with Rough Bottom
C = 65
These curves are for Fairway with 27.0 ft minimum clear depth
Note that elevation of Lake Erie has slight effect on drop at Regulating Works with a given discharge as compared with the effect of roughness of bottom of "Fairway" or change in Chezy coefficient "C".
CURVES OF DISCHARGE THRU FAIRWAY
for various elevations of Upper Pool and with Lake Erie at proposed reg. mean stage El. 574.4

DROP THROUGH WORKS WITH WEIR GATES WIDE OPEN

The next diagram shows the drop from upstream to downstream side of gates when all are wide open, corresponding to various elevations in Lake Huron and while various quantities are discharging with Lake Erie at El. 574.5, or its mean stage.

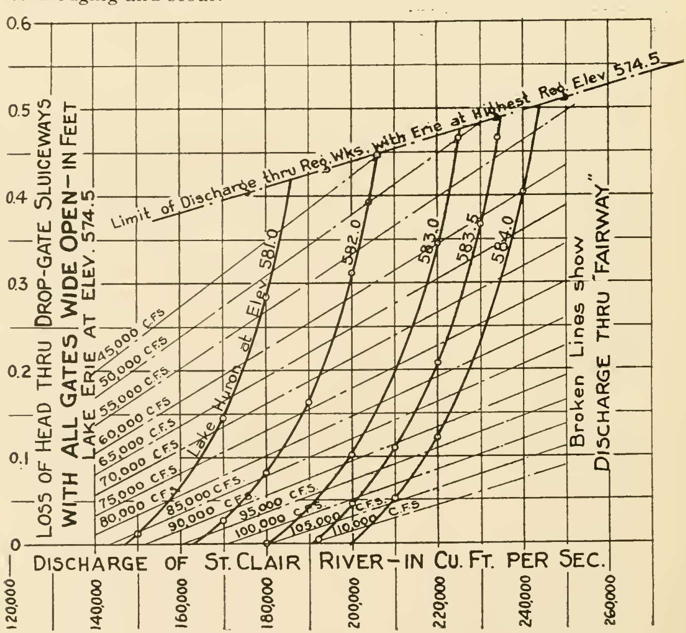
This diagram shows that under the maximum discharge possible (prior to dredging the narrow outlet of Lake Huron to greater width) with

Lake Huron at its maximum regulated high water	El.	583.5 ft.
Lake Erie at its maximum regulated high water	El.	574.5 ft.
Thus giving a total fall between Huron and Erie of		9.0 ft.
With all sluice gate weirs wide open, discharging		185,000 c.f.s.
With Fairway discharging		50,000 c.f.s.
And a discharge down St. Clair and Detroit Rivers of		235,000 c.f.s.
The drop through gates, locks and fairway will be only		0.48 ft.

Note that normal operating conditions for maintenance of high lake levels and accumulation and release of storage, require that gates be more or less closed except under extraordinary flood conditions.

One purpose of this diagram is to show that Regulating works need cause no important obstruction to large discharge in time of flood.

This small drop or obstruction due to Regulating Works when gates are all wide open is barely enough to compensate for either the lowering of Lakes Huron and Michigan due to Chicago diversion, or the lowering due enlargement of the St. Clair Channel, between 1894 and 1910, due to dredging and scour.



The following table shows for various representative conditions, of summer and winter, of flood stages, of ordinary stages and of low stages:

(1) The Rate of Discharge through the St. Clair River.

(2) The drop, or lift, at the Navigation Locks.

(3) The Velocity at the throat of the fairway, in miles per hour.

(4) The Velocity of approach to the fairway.

Under the average water yield of the St. Clair River for the past 25 years (175,000 c.f.s.), with lakes at their mean regulated stages, it is found that
The lift at the locks would be..3.2 ft.
The velocity at throat of fairway would be........................7.3 miles per hour
The velocity of current approaching or leaving fairway..........2.78 ft. per second
Equivalent to..1.9 miles per hour

This absorption of 3.2 ft. out of the 8.0 ft. of total drop between Lake Huron and Lake Erie by the lift at the locks, leaving only 4.8 feet slope in the 80 miles of river channel, will obviously lessen to an important degree the swift current of about 5 miles per hour which now exists in the narrow gorge at the outlet of Lake Huron.

LIMITING AND REPRESENTATIVE CONDITIONS OF REGULATION OF ST. CLAIR RIVER

Flow thru St Clair River	Drop at Regu-lating Works	Discharge thru Fairway	Velocity in throat of Fairway	Discharge thro Regulating Gates	Elevation of Lake Huron	Elevation of Upper Pool	Elevation of Lake Erie	Elevation of Lower Pool	Approx. Veloc. of approach to Fairway	Conditions of Regulation
Cu. Ft per Sec	Feet	Cu Ft per Sec	Miles per Hr	Cu Ft per Sec	Feet above Sea	Feet above Sea	Feet above Sea	Feet above Sea	Feet per Sec	
175,000	3.20	107,000	7.30	68,000	582 8	581.15	574.4	577.95	2.78	Mean flow for 25 years 1900–1924 incl. with Lake Huron and Lake Erie at regulated mean stages.
165,000	3.70	113,000	7.79	52,000	582.8	581.35	574.4	577.62	2.60	Proposed long term mean regulated flow with Lake Huron and Lake Erie at regulated mean stages
215,000	1 43	80,000	5.18	135,000	583.2	580.73	574 5	579.30	3.50	Summer condition or average for Sept. while reinforcing Niagara discharges from storage in Huron, Mich. and Superior
239,000	0.70	57,000	3.61	162,000	583.5	580.42	573 0	579 72	3.89	Maximum discharge with Lake Huron at H W and Lake Erie at L. W. **All gates wide open.**
235,000	0 48	48,000	3.06	187,000	583.5	580.06	574.4	579. 58	3.88	Maximum discharge with Lake Huron at H W and Lake Erie at reg. mean stage **All gates wide open.**
207,000	0 45	45,000	2.93	162,000	582.0	579 40	574.4	578.95	3.51	Maximum discharge with Lake Huron at L.W and Lake Erie at reg mean stage **All gates wide open.**
212,000	0.65	52,000	3.42	160,000	582.0	579 25	573.0	578.60	3.60	Maximum-discharge with Lake Huron at L.W and Lake Erie at L.W. **All gates wide open.**
136,000	5.82	136,000	9 68	0	583.5	582.60	574.4	576.78	2.05	While accumulating storage in closed navigation season, minimum regulated flow with Huron at H W. and Erie at mean stage. **All gates closed.**
121,000	4 82	121,000	8.75	0	582.0	581.15	574.4	576.33	1.92	In closed navigation season, minimum reg. flow with Huron at L W and Erie at mean stage. **All gates closed.**
180,000	3.28	108,000	7.32	72,000	583 0	581.30	574 4	578.10	2 84	Long term mean regulated flow during 8 months of navigation season Apr.-Nov. inclusive.

Note – At or near end of navigation season, Nov 15–Dec 15, regulating gates would be closed permitting Erie to draw down while maintaining the full winter regulated flow in Niagara River.

In early spring the inflow from Erie water-shed plus the flow thru the St Clair fairway will supply all that is required at Niagara and aid in refilling Erie, permitting accumulation of storage to be continued for more or less weeks according to prevailing rainfall.

Whenever in the spring, at some predetermined time, it is desired the St. Clair gates can be opened wide raising Erie a foot or more to H.W. level 574.5 within a very few weeks.

DESIGN OF LOCKS

In all these plans of regulating works at Niagara and at St. Clair the designs have been carried through the stage where contracts at unit prices for construction could be made forthwith, upon the basis of the drawings presented. This has been done in order to remove doubts as to the sufficiency of the estimates of cost and in order to make it easy for critics to check them, as well as for making certain of the feasibility of the designs in all their main details.

Detailed designs for locks in the St. Clair River are presented in Sheets Nos. 7, 8, 9, 10, 11, and 12, pages 336 D to 336 I. It is believed these represent in every respect all of the good points of the best modern practice. Particular attention is called to the devices for the rapid filling and rapid emptying of lock with a minimum of surging and disturbance. This is done by providing exceptionally large passageways for filling and empyting and by distributing the discharge into the lock through a multitude of relatively small nozzles in the lift wall, so as to give great uniformity of gentle entrance current all of the way across. This is illustrated in detail on Sheet No. 9.

Particular attention also has been given to the design of the gates for filling and emptying the lock. Cylinder gates have been adopted, placed high, so as to be quickly accessible for repairs or for the removal of obstruction.

The fall from the upper side to the lower side of the lock is so small in comparison with that at Sault Ste. Marie, that no such elaborate precautions are necessary here as those at the Sault, for closing off the flow in case a lock gate should be rammed and broken away by a boat out of control. No special cofferdam structure for closure in case of broken gates has been provided, but in place of this a secondary emergency gate is provided, which is designed of sufficient strength so that it could be released for full closure under the existing head, one gate at a time, without danger of being broken by the rush of water.

It will be noted that care has been taken in the designs to provide for permitting unwatering of every chamber by means of ample pumps, electrically driven, and placed at a low level, and that subways with convenient stairways are provided for emergency use in passing beneath the locks.

Drawings are presented in sufficient detail so that those familiar with such designs will require no further description.

POSSIBILITIES OF COMBINING A BRIDGE WITH REGULATION WORKS

The highway bridge which was an important feature at Niagara, and which there interposed no obstacle to navigation, being located down-stream from all passage of boats, would perhaps be deemed inadmissible on the St. Clair River.

The writer believes it possible to design quick-moving bascule bridges for this location which would not necessarily present any important obstruction to navigation if the burden of delay were imposed always on road traffic and never on boats.

On Sheet No. 13 a cross-section of a wide bridge having beneath it head room sufficient for small boats is outlined to show how this would stand in general relation to the gates. The low level bridge would save two million dollars and certainly be more convenient. The non-navigation season comprises about one-third of the entire year.

The type of high bridge recommended is shown in Sheet No. 14, where the concrete arches necessary for stiffening the tops of the piers between the gates, which are made thin to lessen their obstruction to masses of floating ice, form a bridge over the gates to be used for maintenance and operating purposes, and which is narrowed up so as to give a passage way only 20 feet in width, sufficient for locomotive cranes for lifting out or setting gates, and for motor trucks, whenever repairs become necessary on any of the gates, and is continuous excepting over the locks.

Supports are provided on both sides of these arch-piers for a future high level steel bridge, the outline of which is shown in Sheet No. 15. This steel superstructure can be added at any time without interruption of any kind to the regulation works, or to the passage of ships through locks or fairway.

The additional cost of this elevated steel bridge and its piers and long approaches is estimated at three million dollars. It is recommended that the pier bases be built at the same time with the locks and sluiceways, in readiness for future demands for such a bridge having a type of piers giving a minimum obstruction of views.

A type of design of tall cylindrical piers has been outlined, that would present the least possible obstruction of view to pilots in either direction. This is particularly important to a boat proceeding downstream swiftly toward the fairway.

DESIGNS OF SLUICES AND GATES

These are of the same general type proposed for Niagara River in this report, but modified in form and size to meet the local conditions of the St. Clair River.

The gates are of the same drop-weir type proposed for the Niagara Regulation Works. This type presents many advantages over the Stoney Gate, in beauty of appearance of the entire structure, in facility for operation and repair, and in freedom from depreciation through corrosion. Also it presents a great advantage in that it can be quickly laid flat on the bed of the river, with a clear space over it, within which ice or other obstruction can pass. Any one gate can readily be lifted out or reset by a pair of locomotive cranes or by floating crane. Moreover in the worst conceivable emergency, if desirable, under any conditions of interruption of electric power, any or all gates can quickly be laid at the bottom, wide open, either by operating the winch by hand, or by cutting the corner chains with an electric or acetylene torch.

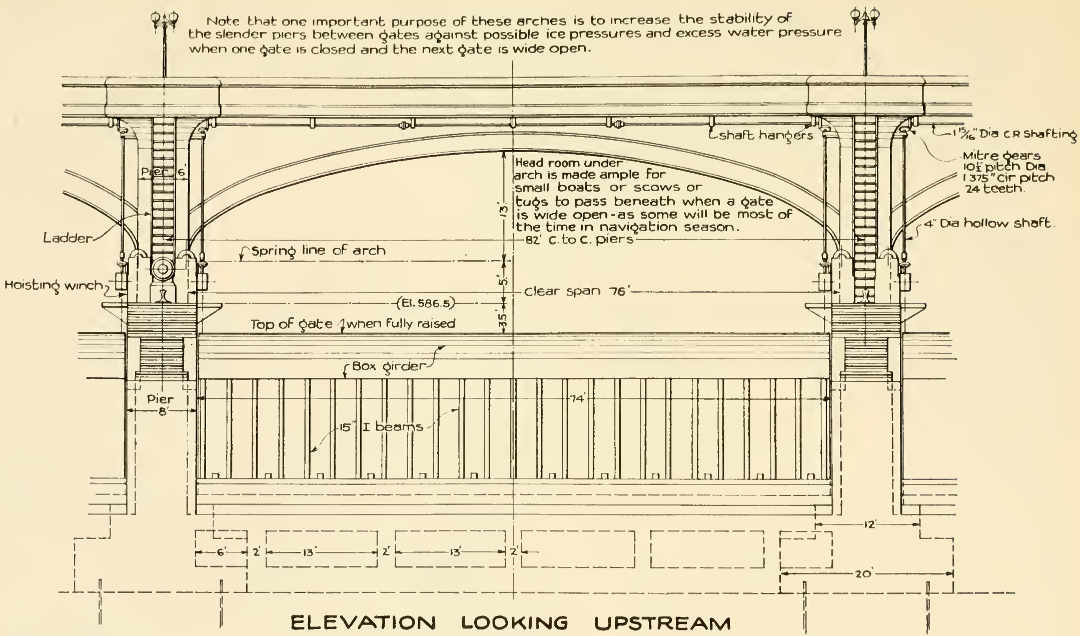
LOCK-FILLING DEVICES

The writer, in observing the operation of many locks, has been impressed with an idea that the hydraulic arrangements could be improved, and has ventured to incorporate two features out of the ordinary, neither of which is his own invention.

(1) The Cylinder Gate, which was an admirable device used by some of the New England millwrights of a century ago. It presents a perfect balance, is inexpensive and remarkably accessible.

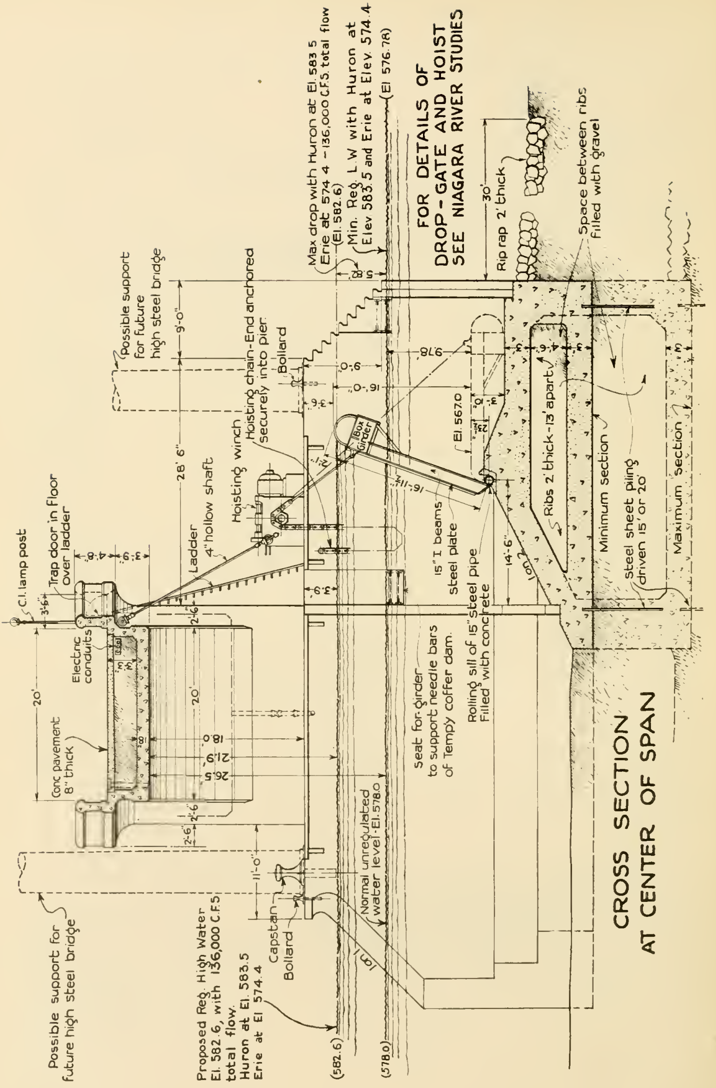
(2) A device developed by the eminent hydraulic expert, Professor G. de Thierry, of the Engineering School at Charlottenberg, by remarkably extensive experiments on large scale models in the Hydraulic Laboratory, for use in a new lock of largest size in Holland.

This presents great economies in construction by avoiding nearly all water passages in side walls and floors, and gives a wonderful freedom from swirls and commotion inside the lock, while filling at a rapid rate. Obviously, Dr. de Thierry should be consulted before putting this device into practical use. The drawing is merely the present writer's working out of Dr. de Thierry's ideas.



ELEVATION LOOKING UPSTREAM

Scale of Feet



CROSS SECTION
AT CENTER OF SPAN
FOR DETAILS OF
DROP-GATE AND HOIST
SEE NIAGARA RIVER STUDIES
Possible support for
future high steel bridge
Possible support
for future
high steel bridge
Proposed Reg. High Water
El. 582.6, with 136,000 C.F.S.
total flow.
Huron at El. 583.5
Erie at El 574.4
Max drop with Huron at El. 583.5
Erie at 574.4 – 136,000 C.F.S. total flow
(El. 582.6)
Min. Reg. L.W with Huron at
Elev 583.5 and Erie at Elev. 574.4
(El 576.78)
(582.6)
(578.0)
Normal unregulated
water level-El. 578.0
C.I. lamp post
Trap door in Floor
over ladder
Conc pavement
8" thick
Electric
conduits
Ladder
4" hollow shaft
Hoisting winch
Hoisting chain-End anchored
securely into pier
Bollard
Capstan
Bollard
Box
Girder
15" I beams
Steel plate
Rolling sill of 15" Steel pipe
Filled with concrete
Seat for girder
to support needle bars
of Temp'y coffer dam.
El. 567.0
Rip rap 2' thick
Space between ribs
filled with gravel
Ribs 2' thick-13' apart
Minimum Section
Steel sheet piling
driven 15' or 20'
Maximum Section
20'
28' 6"
9'-0"
11'-0"
14'-6"
30'

CONSTRUCTION PROGRAM AND ARRANGEMENT OF COFFER-DAMS

The proposed method of construction is indicated upon St. Clair Sheet No. 17, on the preceding page. The first operation would be an enclosure of most of the American half of the site in the river by one large coffer-dam, within which the American lock and the American sluices would be constructed. The westerly wall of the fairway would form a part of this coffer-dam. (See page 336 L.)

The guard piers for the locks and for the fairway would be outside this coffer-dam and might readily be formed by moving to the new position the caissons of which coffers Nos. 1 and 3 are composed.

Coffer-dams for this depth of water, and in this current, present interesting problems and in order to show that the whole problem of building these works has been worked through to the practical construction stage, a design for the coffer-dam on which the estimates of cost are based, is shown in Sheet No. 17.

This design presents some novel features. The coffer-dam as a whole is composed of a series of floating caissons, each of which would be built upon a large scow, similar in all respects to the carfloats formerly in common use for ferrying cars across the St. Clair and Detroit Rivers, or such as are used in New York Harbor. The ends of this float would be equipped with derricks by which the timber caisson could be launched over the stern, or over the side of the float, and then warped into precise position, interlocked with its neighbor, loaded with more ballast, and then pinned down to the bed of the river by two large reinforced concrete piles, jetted into position somewhat after the method adopted by Wood Brothers, of Omaha, in building their dikes in the Missouri River. The individual caisson would be filled with sand or small gravel, to give sufficient weight against overturn when the water pressure on one side is subsequently removed.

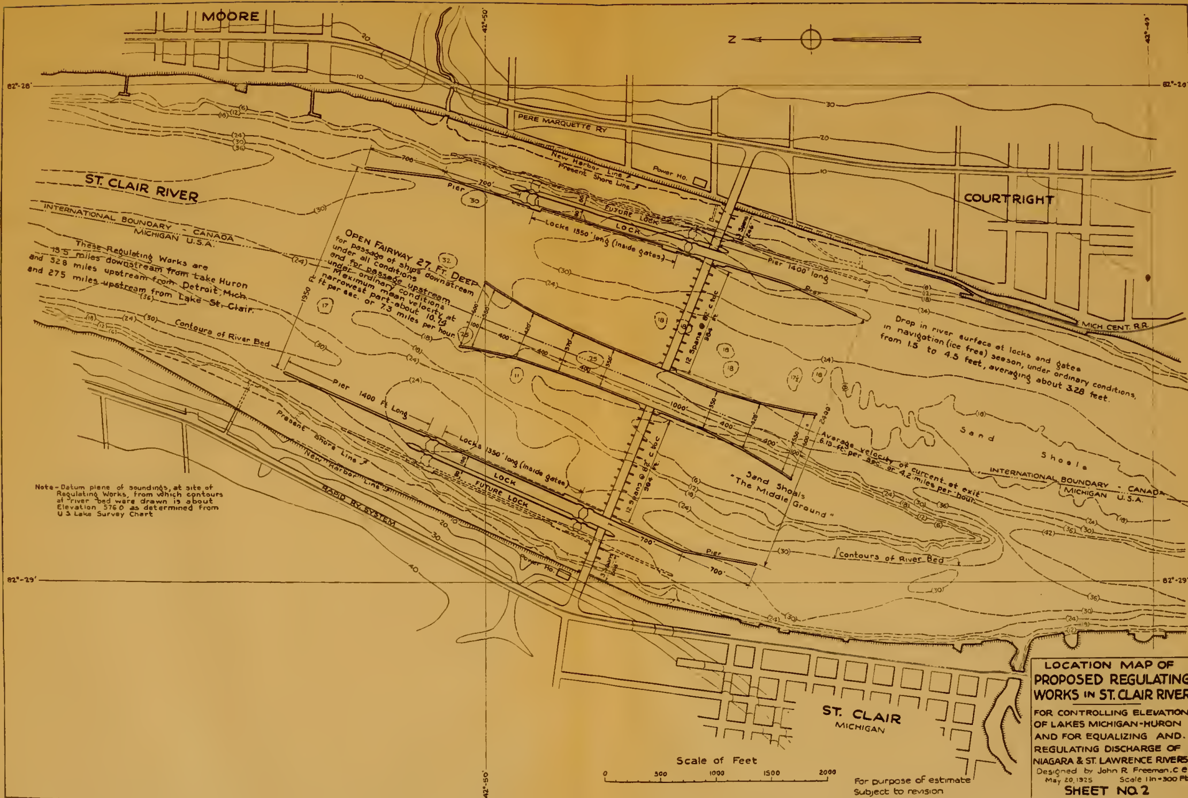
In order to unite these caissons to the bed of the river with a tight joint, and, to in every way increase their permanent stability, it is proposed that their base be guarded on each side by a line of interlocking steel sheet piling, as illustrated on page 337; and it is further proposed that after the piling for each caisson has been driven to its full depth that the space left between the river bed and the bottom of the caisson be pressure-grouted with a mixture of sand and cement, forced down by air pressure from above, in the customary way. It will be noted that the preliminary weighting of the caisson is effected by a thin concrete floor turned up at the edges, which serves both for ballast and for giving rigidity.

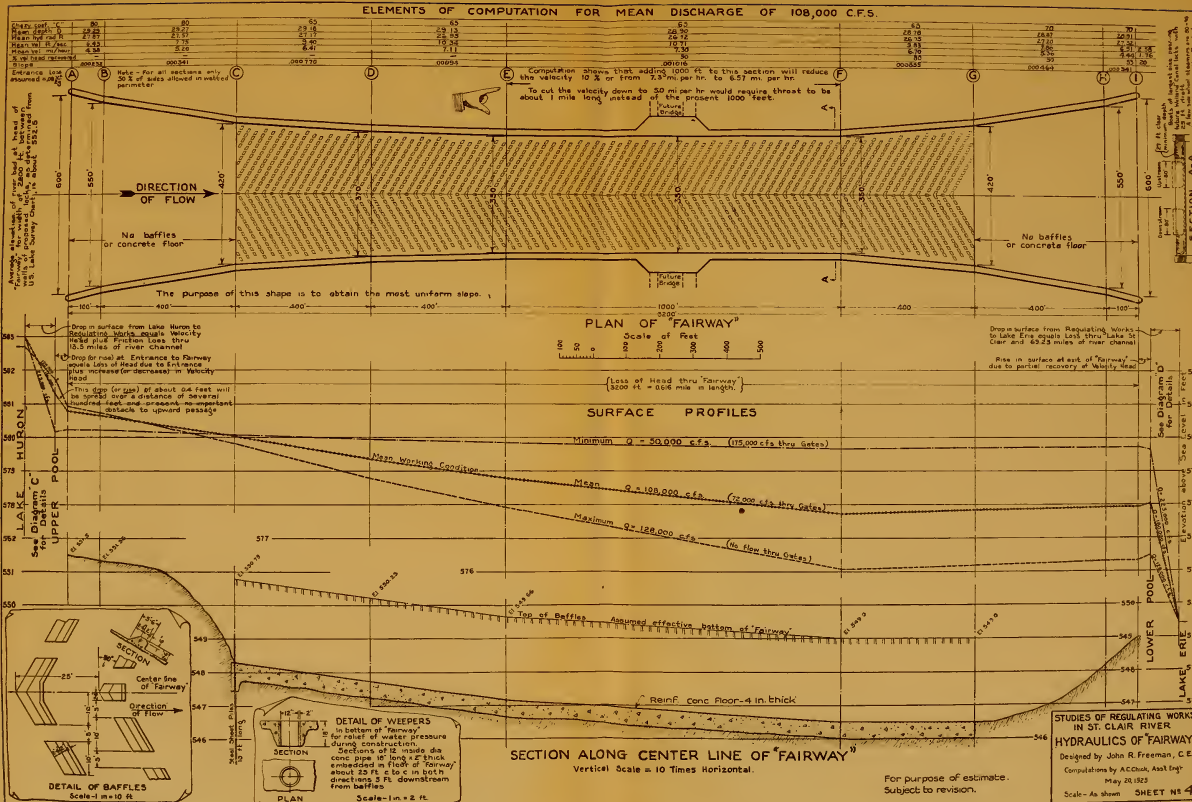
Some parts of these coffer-dams, for example the caissons along the fairway, would be left permanently in position to form a part of the completed structure and would be capped by concrete above the water line. If thought best the filling of these permanent caissons could be made with rubble, and this could, in part, be pressure-grouted with a lean mixture of sand and cement.

The temporary caissons, such as those in coffers Nos. 1 and 3 and Nos. 7 and 8, when first placed would be filled with fine gravel, so that this could be removed by grab-bucket or suction pump, and the caisson pumped out and floated for moving to a new location. It could be either elevated off its two concrete piles, or these piles could be sunk by water jet to still greater depths, so as to leave the caisson free for floating and towing to its new location.

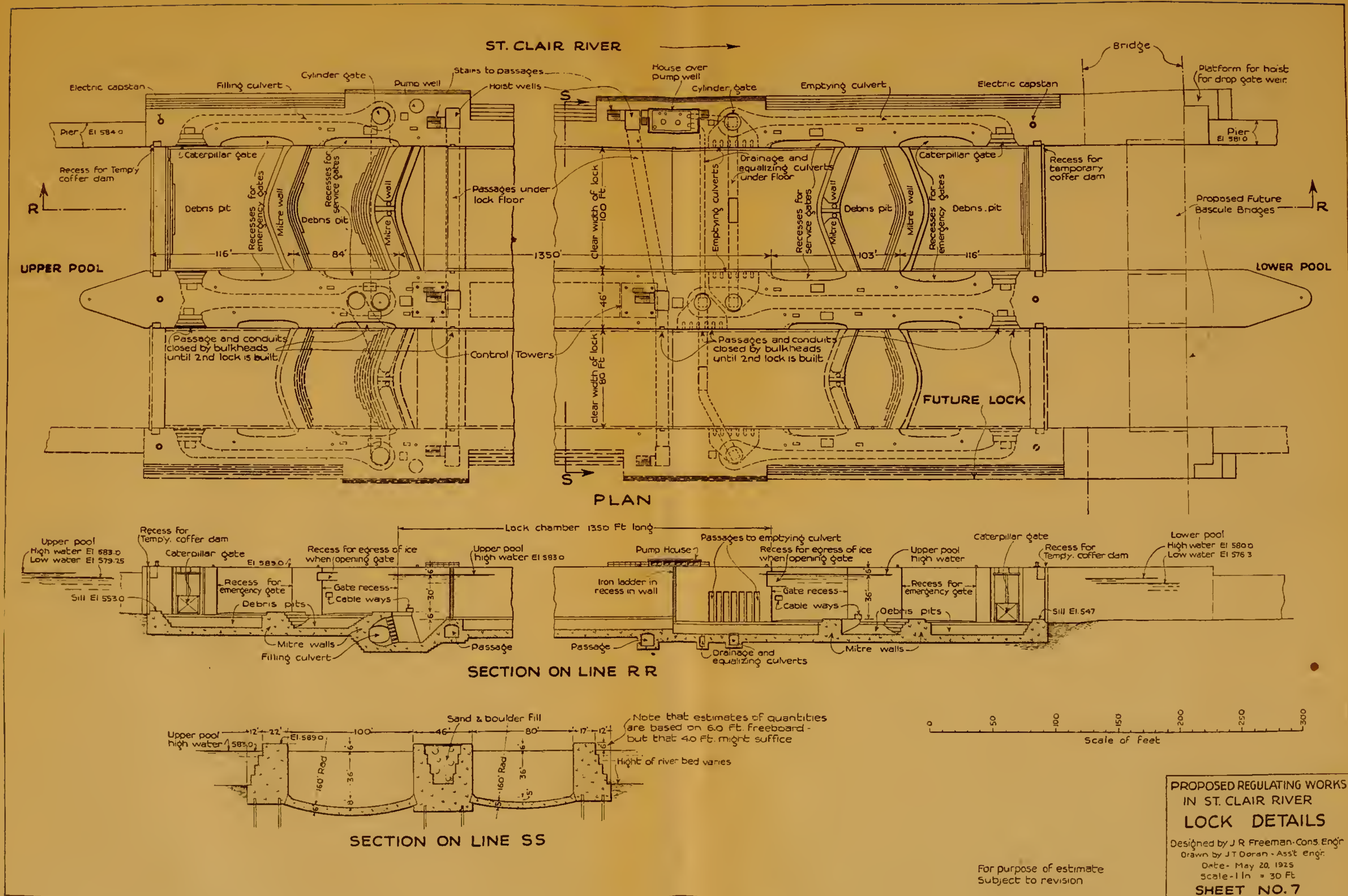
Attention may be called to the preceding sketches showing methods for effecting economies in length of steel sheet piling and for facilitating driving this steel piling in close contact with the edge of the coffer. The small space between the face of steel piles and the face of the plank would be made tight by pieces of plank cut to fill this space and nailed to the main planking prior to suspending the piles and prior to launching.

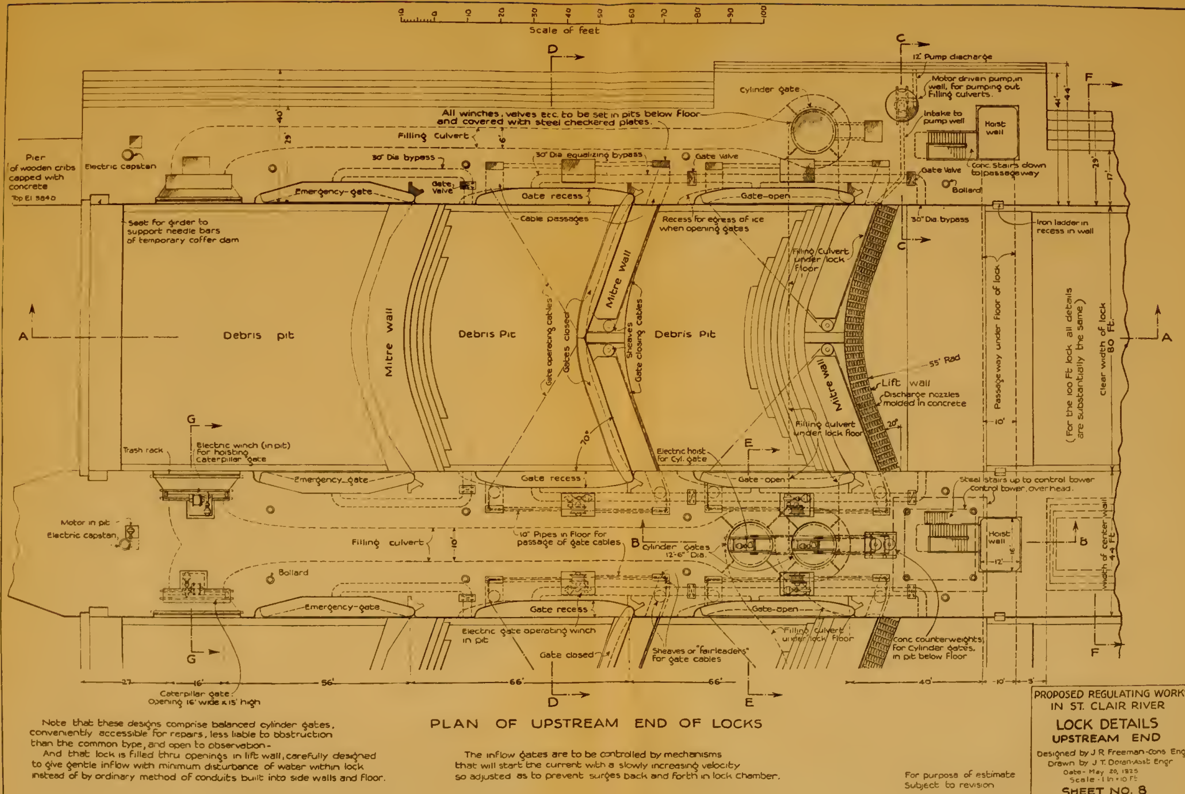
PROPOSED REGULATING WORKS ST. CLAIR SITE
LAKE HURON
PROVINCE OF ONTARIO
LAKE ST. CLAIR
WALPOLE ISLAND
ALTERNATE SITE FOR REGULATING WORKS
LAKE ERIE
STATE OF MICHIGAN
Depths are measured below Elev 578.50
Depths are measured below Elev 575.16
Depths are measured below Elev 570.0
International Boundary
Sarnia
Port Huron
Marysville
St. Clair
Marine City
Algonac
Windmill Point
Detroit
Amherstburg
Wyandotte
Gibraltar
Grosse Isle
Livingstone Channel
Scale of Feet
Statute Miles
Distance in Miles from Fort Gratiot Light-House
SUBJECT TO REVISION
POSSIBILITIES OF PLACING THE REGULATING WORKS NEAR WINDMILL POINT SHOULD BE STUDIED
LAKE ST. CLAIR
High Water of 1838
Proposed Regulated H W
Proposed Regulated L W
Mean Stage 1860-1921 incl.
Lowest recorded monthly mean Feb. 1925-578.10
Approx. HW with Reg Wks. at Windmill Point
El. 577.86 High Water of 1838
El. 575.58 Mean Stage 1860-1925 incl.
El. 573.14 Jan 1926—Lowest recorded monthly mean
Profile of Water Surface June 26th - July 1st 1899
Profile of Water Surface Oct 10th - Oct 15th 1898
These profiles are mainly from observations of 1898 and 1899 given in Deep Waterways Report of 1900, and Chief of Army Engineers' Report of 1900, Appendix III, page 5368
DETROIT
Note - It is reported that under extreme conditions of High Water in Lake Erie due to ice gorges or wind (seiches) that current opposite Detroit has flown upstream for brief period.
Note that this would call for a rise in Lake Erie of only 3 or 4 feet.
The storage effect of Lake St Clair will compensate for the extreme effect of seiches in Lake Erie so these will not affect height of water surface at Regulating Works to any important extent.
Seiches in Lake Huron will in a large degree be transmitted to Regulating Works.
575.11 High Water of 1838
574.5 Proposed Regulated H W
573.0 Proposed Regulated L W
572.49 Mean Stage 1860-1925 incl.
570.50-Feb. 1925 Lowest recorded monthly mean.
DIAGRAM ILLUSTRATING APPLICATION OF FORMULA FOR COMPUTING DISCHARGE
Surface Profile of June 26 - July 1, 1899 204,900 c.f.s.
ST. CLAIR RIVER
LAKE ST CLAIR
DETROIT RIVER
Mean depths are taken from Chief of Army Engrs Report Appendix FFF, page 2840 and Appendix EEE, page 4084, also from U S Lake Survey Charts
Scale Horiz. 1 in = 10 mi. Vert. 1 in = 10 ft
The chief purpose of this diagram is to show the influence of Elevation of Lake Erie upon the Elevation of Lake Huron, and that because of Lake Erie being so high above river bed at outlet of Lake Huron.
The discharge of combined St Clair and Detroit Rivers is similar to that over a deeply submerged weir with a crest 83 miles broad and a submergence more than double the effective head.
Mean Coeff in Chezy Formula V = C√RS
For 13 miles above Reg Wks. C = 97.
For 53 miles below Reg. Wks. C = 87-91
Bottom presumably, smooth sand or clay
Note the great depth, below the surface of Lake Erie, of the sill over which the discharge of Lake Huron takes place.
STUDIES OF REGULATING WORKS IN ST. CLAIR RIVER
LOCATION MAP AND RIVER SURFACE PROFILE L. HURON TO L. ERIE
Designed by John R. Freeman, C.E.
A C Chick, Asst Engr
May 20, 1925
Scale - Various
SHEET No 1


MOORE
COURTRIGHT
ST. CLAIR RIVER
INTERNATIONAL BOUNDARY - CANADA
MICHIGAN U.S.A.
PERE MARQUETTE RY
MICH. CENT. R.R.
RAPID RY. SYSTEM
ST. CLAIR
MICHIGAN
These Regulating Works are 13.5 miles downstream from Lake Huron and 328 miles upstream from Detroit, Mich. and 275 miles upstream from Lake St. Clair.
OPEN FAIRWAY 27 FT. DEEP for passage of ships downstream under all conditions and for passage upstream under ordinary conditions
Maximum mean velocity at narrowest part about 10.74 ft per sec. or 7.3 miles per hour
Drop in river surface at locks and gates in navigation (ice free) season, under ordinary conditions, from 1.5 to 4.5 feet, averaging about 3.28 feet.
Average velocity of current at exit 6.13 ft per sec. or 4.2 miles per hour
Sand Shoals "The Middle Ground"
Sand Shoals
Contours of River Bed
Locks 1350' long (Inside gates)
Pier 1400' long
Pier 1400 Ft Long
FUTURE LOCK
LOCK
Power Ho.
New Harbor Line
Present Shore Line
Note - Datum plane of soundings, at site of Regulating Works, from which contours of river bed were drawn is about Elevation 576.0 as determined from U.S. Lake Survey Chart
Scale of Feet
0 500 1000 1500 2000
For purpose of estimate
Subject to revision
LOCATION MAP OF PROPOSED REGULATING WORKS IN ST. CLAIR RIVER
FOR CONTROLLING ELEVATION OF LAKES MICHIGAN-HURON AND FOR EQUALIZING AND REGULATING DISCHARGE OF NIAGARA & ST. LAWRENCE RIVERS
Designed by John R. Freeman, C.E.
May 20, 1925
Scale 1 In.=300 Ft.
SHEET NO. 2

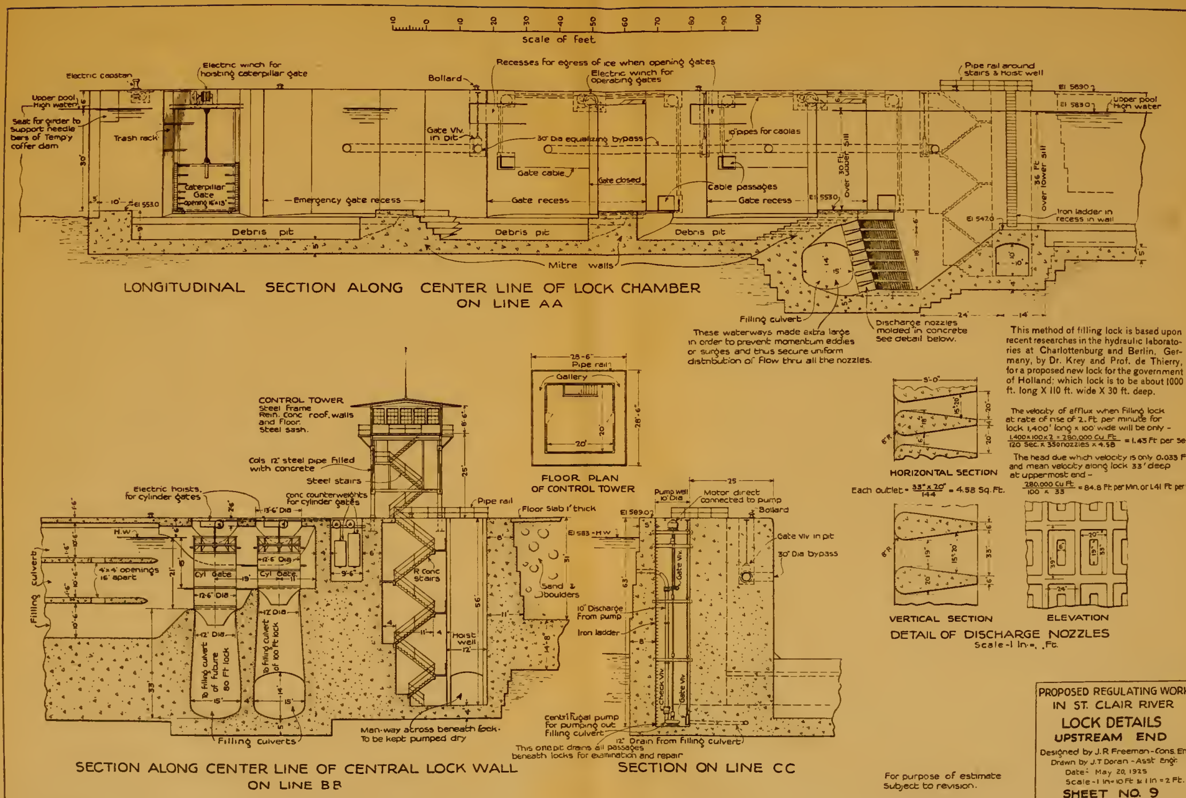


ELEMENTS OF COMPUTATION FOR MEAN DISCHARGE OF 108,000 C.F.S.
Note - For all sections only 50 % of sides allowed in wetted perimeter
Computation shows that adding 1000 ft to this section will reduce the velocity 10 % or from 7.3 mi. per hr. to 6.57 mi. per hr.
To cut the velocity down to 5.0 mi per hr would require throat to be about 1 mile long instead of the present 1000 feet.
Future Bridge
DIRECTION OF FLOW
No baffles or concrete floor
The purpose of this shape is to obtain the most uniform slope.
PLAN OF "FAIRWAY"
Scale of Feet
SECTION A-A
Drop in surface from Lake Huron to Regulating Works equals Velocity Head plus Friction Loss thru 13.5 miles of river channel
Drop (or rise) at Entrance to Fairway equals Loss of Head due to Entrance plus increase (or decrease) in Velocity Head
Drop in surface from Regulating Works to Lake Erie equals Loss thru Lake St Clair and 69.23 miles of river channel
Rise in surface at exit of "Fairway" due to partial recovery of Velocity Head
Loss of Head thru "Fairway" 3200 ft = 0.616 mile in length.
SURFACE PROFILES
Minimum Q = 50,000 c.f.s. (175,000 cfs thru Gates)
Mean Working Condition
Mean Q = 108,000 c.f.s. (72,000 cfs thru Gates)
Maximum Q = 128,000 cfs (No flow thru Gates)
LAKE HURON
UPPER POOL
LOWER POOL
LAKE ERIE
Top of Baffles
Assumed effective bottom of "Fairway"
Reinf. Conc Floor-4 in. thick
Steel Sheet Piles 10 ft long
DETAIL OF BAFFLES
Scale-1 in = 10 ft
Center line of "Fairway"
Direction of Flow
DETAIL OF WEEPERS
In bottom of "Fairway" for relief of water pressure during construction.
Sections of 12 inside dia conc pipe 18" long x 2" thick embedded in floor of "Fairway" about 25 ft c to c in both directions 5 ft downstream from baffles
SECTION
PLAN
Scale-1 in. = 2 ft.
SECTION ALONG CENTER LINE OF "FAIRWAY"
Vertical Scale = 10 Times Horizontal.
For purpose of estimate. Subject to revision.
STUDIES OF REGULATING WORKS IN ST. CLAIR RIVER
HYDRAULICS OF "FAIRWAY"
Designed by John R. Freeman, C.E.
Computations by A.C.Chick, Asst Engr
May 20, 1925
Scale - As shown
SHEET No 4

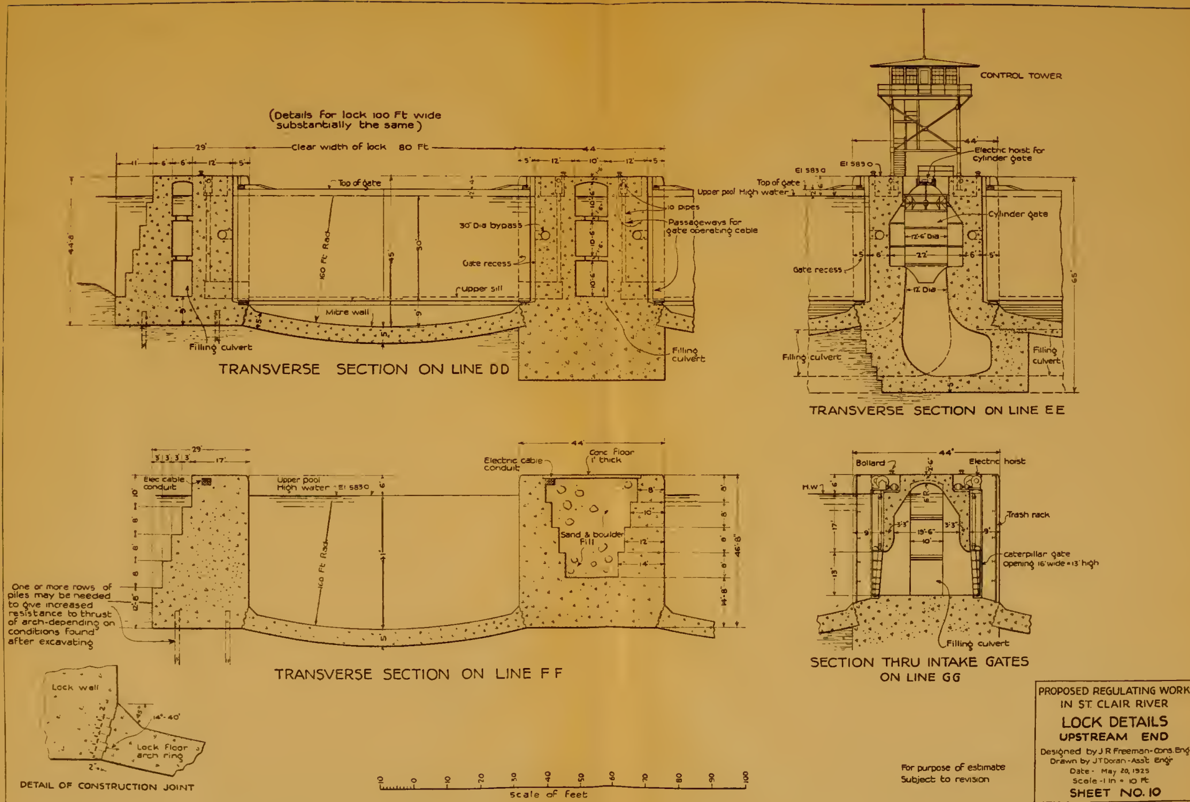

ST. CLAIR RIVER
UPPER POOL
LOWER POOL
Electric capstan
Filling culvert
Cylinder gate
Pump well
Stairs to passages
Hoist wells
House over pump well
Emptying culvert
Bridge
Platform for hoist for drop gate weir
Pier El 584.0
Pier El 581.0
Caterpillar gate
Recess for Temp'y coffer dam
Recess for temporary coffer dam
Debris pit
Recesses for emergency gates
Mitre wall
Recesses for service gates
Passages under lock floor
Clear width of lock 100 Ft.
Clear width of lock 80 Ft.
Drainage and equalizing culverts under floor
Emptying culverts
Proposed Future Bascule Bridges
116'
84'
1350'
103'
46'
Passage and conduits closed by bulkheads until 2nd lock is built
Control Towers
FUTURE LOCK
PLAN
Lock chamber 1350 Ft long
Upper pool High water El 583.0 Low water El 579.25
Recess for Temp'y. coffer dam
El 583.0
Recess for egress of ice when opening gate
Upper pool high water El 583.0
Recess for emergency gate
Gate recess
Cable ways
Debris pits
Sill El 553.0
Mitre walls
Filling culvert
Passage
Pump House
Iron ladder in recess in wall
Passages to emptying culvert
Upper pool high water
Drainage and equalizing culverts
Lower pool High water El 580.0 Low water El 576.3
Sill El. 547
SECTION ON LINE RR
Upper pool high water 583.0
El. 589.0
Sand & boulder fill
Note that estimates of quantities are based on 6.0 Ft. freeboard - but that 4.0 Ft. might suffice
Hight of river bed varies
SECTION ON LINE SS
Scale of Feet
For purpose of estimate Subject to revision
PROPOSED REGULATING WORKS IN ST. CLAIR RIVER
LOCK DETAILS
Designed by J R Freeman - Cons. Engr
Drawn by J T Doran - Asst Engr
Date - May 20, 1925
Scale - 1 In = 30 Ft
SHEET NO. 7

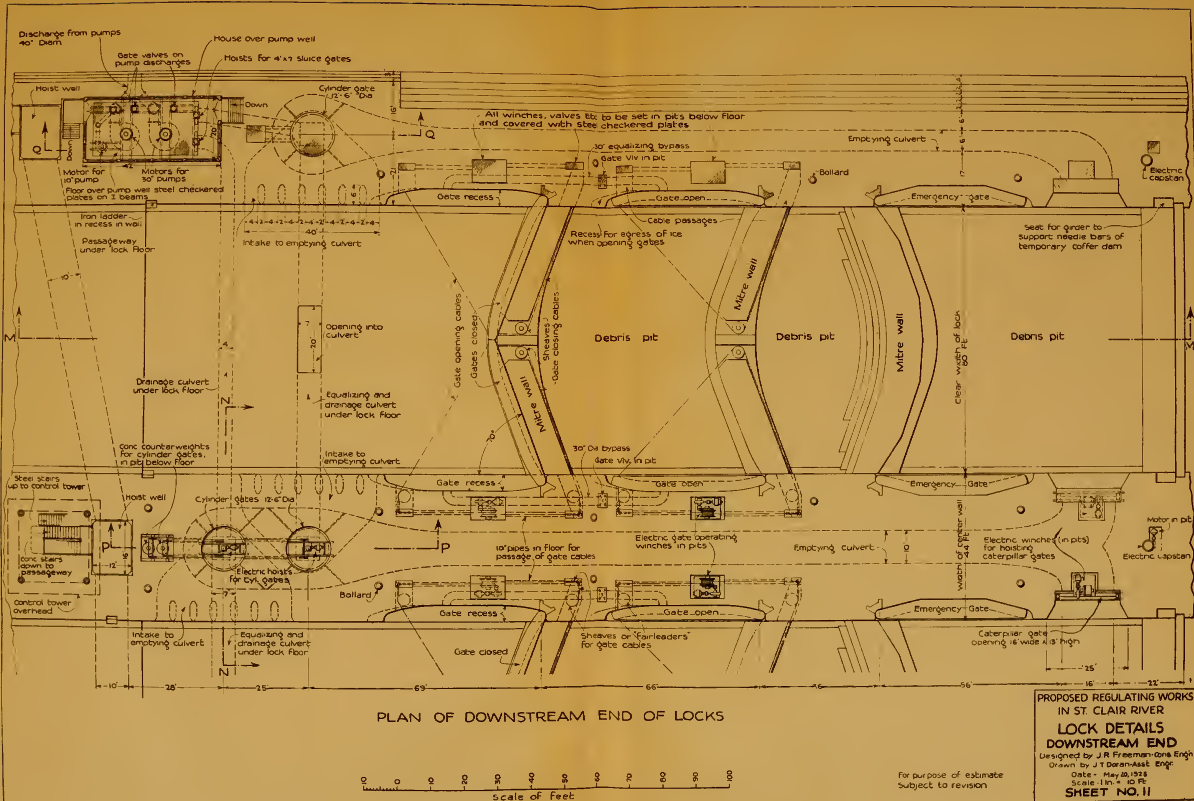


Scale of feet
All winches, valves etc. to be set in pits below Floor and covered with steel checkered plates.
Filling culvert
30" Dia bypass
30" Dia equalizing bypass
Gate valve
Cylinder gate
12" Pump discharge
Motor driven pump, in well, for pumping out Filling culverts.
Intake to pump well
Hoist well
Conc. Stairs down to passageway
Bollard
Pier of wooden cribs capped with concrete
Top El 584.0
Electric capstan
Emergency-gate
Gate Valve
Gate recess
Gate-open
Cable passages
Recess for egress of ice when opening gates
30" Dia. bypass
Iron ladder in recess in wall
Seat for girder to support needle bars of temporary coffer dam
Debris pit
Mitre wall
Debris Pit
Gate operating cables
Gates closed
Sheaves
Gate closing cables
Filling Culvert under lock Floor
55' Rad
Lift wall
Discharge nozzles molded in concrete
Passage way under floor of lock
(For the 100 Ft lock all details are substantially the same)
Clear width of lock 80 Ft.
Filling culvert under lock floor
Electric hoist for Cyl. gate
Trash rack
Electric winch (in pit) for hoisting caterpillar gate
Steel stairs up to control tower
Control tower, overhead.
Motor in pit
Electric capstan
10" Pipes in Floor for passage of gate cables
Cylinder Gates 12'-6" Dia.
Width of center wall 44 Ft.
Electric gate operating winch in pit
Gate closed
Sheaves or "fairleaders" for gate cables
Conc counterweights for Cylinder gates, in pit below floor
Caterpillar gate Opening 16' wide x 15' high
PLAN OF UPSTREAM END OF LOCKS
Note that these designs comprise balanced cylinder gates, conveniently accessible for repairs, less liable to obstruction than the common type, and open to observation.
And that lock is filled thru openings in lift wall, carefully designed to give gentle inflow with minimum disturbance of water within lock instead of by ordinary method of conduits built into side walls and floor.
The inflow gates are to be controlled by mechanisms that will start the current with a slowly increasing velocity so adjusted as to prevent surges back and forth in lock chamber.
For purpose of estimate Subject to revision
PROPOSED REGULATING WORKS IN ST. CLAIR RIVER
LOCK DETAILS
UPSTREAM END
Designed by J R Freeman-Cons Engr
Drawn by J T Doran-Asst Engr
Date - May 20, 1925
Scale - 1 in = 10 Ft
SHEET NO. 8



Scale of Feet
Electric capstan
Electric winch for hoisting caterpillar gate
Bollard
Recesses for egress of ice when opening gates
Electric winch for operating gates
Pipe rail around stairs & Hoist well
El 589.0
El 583.0
Upper pool High water
Seat for girder to support needle bars of Temp'y coffer dam
Trash rack
Gate Vlv. in pit
30" Dia equalizing bypass
10" pipes for cables
Gate cable
Gate closed
Cable passages
Caterpillar Gate opening 16'x13'
Emergency gate recess
Gate recess
El 553.0
El 547.0
Over upper sill
Over lower sill
Iron ladder in recess in wall
Debris pit
Mitre walls
LONGITUDINAL SECTION ALONG CENTER LINE OF LOCK CHAMBER
ON LINE AA
Filling culvert
These waterways made extra large in order to prevent momentum eddies or surges and thus secure uniform distribution of flow thru all the nozzles.
Discharge nozzles molded in concrete See detail below.
This method of filling lock is based upon recent researches in the hydraulic laboratories at Charlottenburg and Berlin, Germany, by Dr. Krey and Prof. de Thierry, for a proposed new lock for the government of Holland; which lock is to be about 1000 ft. long X 110 ft. wide X 30 ft. deep.
The velocity of efflux when Filling lock at rate of rise of 2. Ft. per minute for lock 1,400' long x 100' wide will be only –
1,400 x 100 x 2 = 280,000 Cu Ft / 120 Sec. x 350 nozzles x 4.58 = 1.43 Ft per Sec.
The head due which velocity is only 0.033 Ft. and mean velocity along lock 33' deep at uppermost end –
280,000 Cu Ft / 100 x 33 = 84.8 Ft per Min. or 1.41 Ft per Sec.
HORIZONTAL SECTION
Each outlet = 33" x 20" / 144 = 4.58 Sq. Ft.
VERTICAL SECTION
ELEVATION
DETAIL OF DISCHARGE NOZZLES
Scale-1 In-=, Ft.
CONTROL TOWER
Steel Frame
Rein. Conc roof, walls and Floor.
Steel sash.
Cols 12" steel pipe filled with concrete
Steel stairs
Electric hoists for cylinder gates
Conc counterweights for cylinder gates
Pipe rail
Gallery
FLOOR PLAN OF CONTROL TOWER
Floor Slab 1' thick
Filling culvert
4'x4' openings 16' apart
Cyl Gate
12-6" Dia
12' Dia
To filling culvert of future 80 Ft lock
To filling culvert of 100 Ft lock
R Conc Stairs
Hoist well
Sand & boulders
Pump well 10' Dia
Motor direct connected to pump
Bollard
Gate Vlv in pit
30" Dia bypass
10" Discharge from pump
Iron ladder
Check Vlv
Gate Vlv
Centrifugal pump for pumping out Filling culvert
12" Drain from Filling culvert
This one pit drains all passages beneath locks for examination and repair
Man-way across beneath lock. To be kept pumped dry
Filling culverts
SECTION ALONG CENTER LINE OF CENTRAL LOCK WALL
ON LINE BB
SECTION ON LINE CC
For purpose of estimate Subject to revision.
PROPOSED REGULATING WORKS IN ST. CLAIR RIVER
LOCK DETAILS
UPSTREAM END
Designed by J.R Freeman - Cons. Engr
Drawn by J.T Doran - Asst Engr.
Date: May 20, 1925
Scale - 1 In = 10 Ft & 1 In = 2 Ft.
SHEET NO. 9

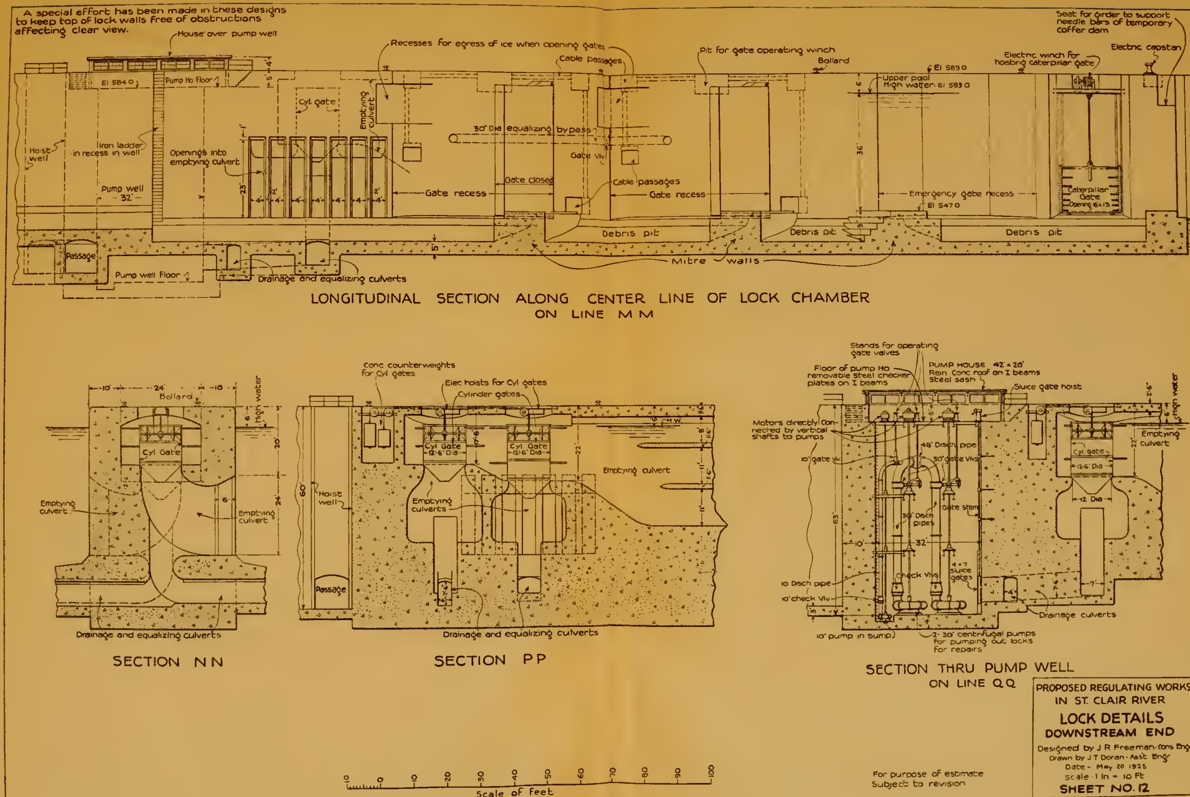

(Details for lock 100 Ft wide substantially the same)
Clear width of lock 80 Ft
Top of gate
30" Dia bypass
Gate recess
Upper sill
Mitre wall
160 Ft Rad
10 pipes
Passageways for gate operating cable
Upper pool High water
Filling culvert
TRANSVERSE SECTION ON LINE DD
CONTROL TOWER
Electric hoist for cylinder gate
El 583.0
Cylinder gate
Gate recess
Filling culvert
TRANSVERSE SECTION ON LINE EE
Elec cable conduit
Upper pool High water - El 583.0
160 Ft Rad
Electric cable conduit
Conc floor 1' thick
Sand & boulder Fill
One or more rows of piles may be needed to give increased resistance to thrust of arch-depending on conditions found after excavating
TRANSVERSE SECTION ON LINE FF
Bollard
Electric hoist
H.W.
Trash rack
caterpillar gate opening 16' wide × 13' high
Filling culvert
SECTION THRU INTAKE GATES ON LINE GG
Lock wall
Lock floor arch ring
DETAIL OF CONSTRUCTION JOINT
Scale of Feet
For purpose of estimate
Subject to revision
PROPOSED REGULATING WORKS IN ST. CLAIR RIVER
LOCK DETAILS
UPSTREAM END
Designed by J R Freeman - Cons. Engr
Drawn by J T Doran - Asst. Engr
Date - May 20, 1925
Scale - 1 in = 10 Ft
SHEET NO. 10



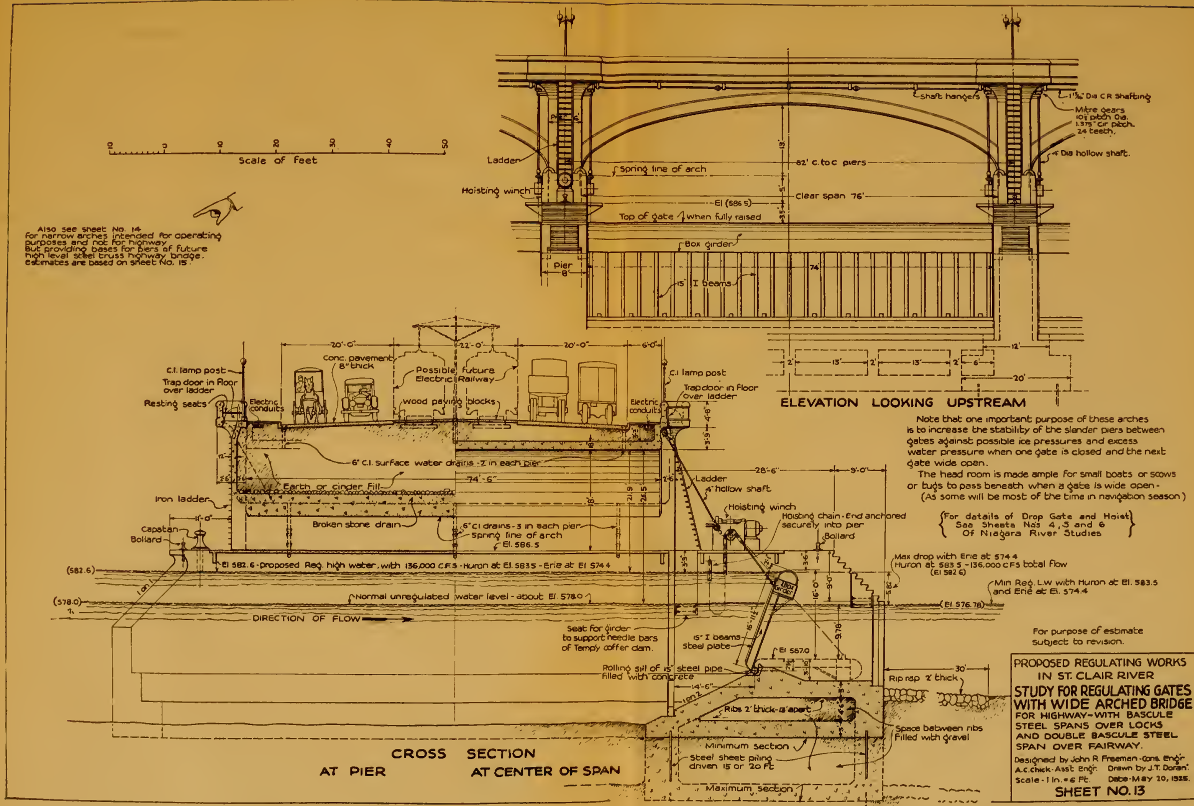
PLAN OF DOWNSTREAM END OF LOCKS

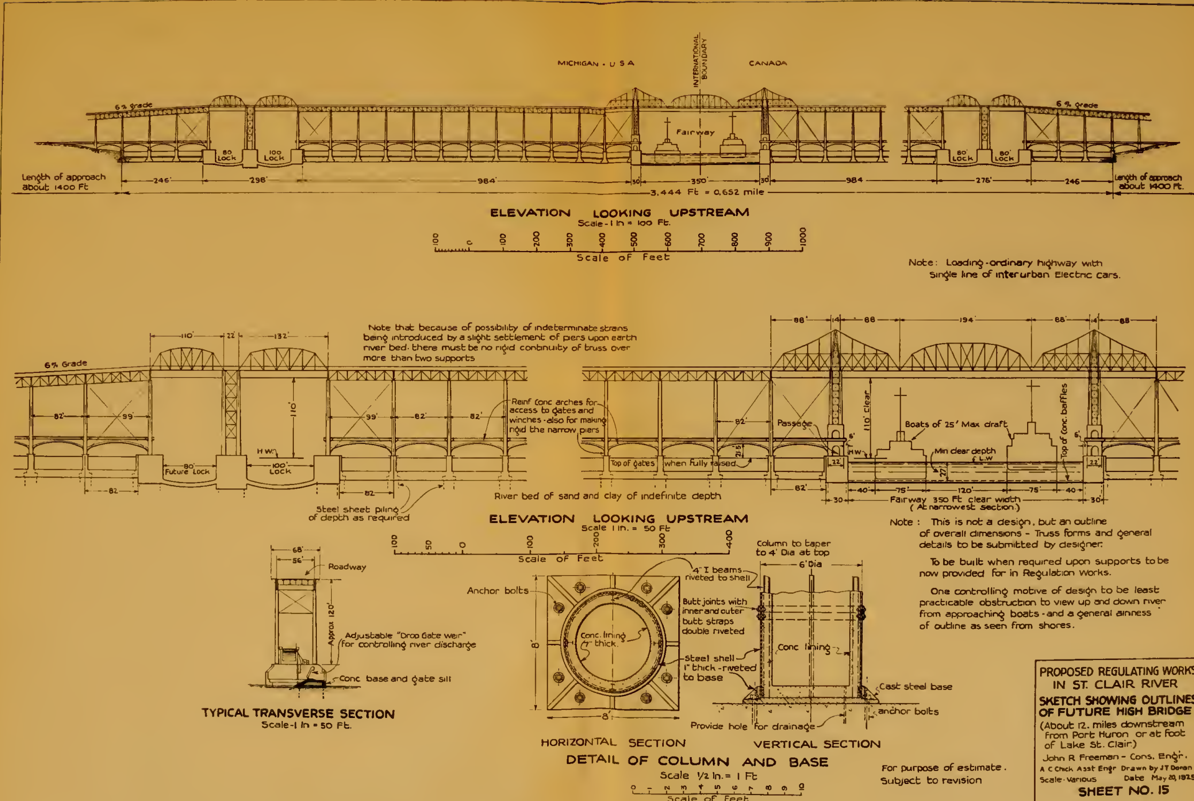
For purpose of estimate
Subject to revision

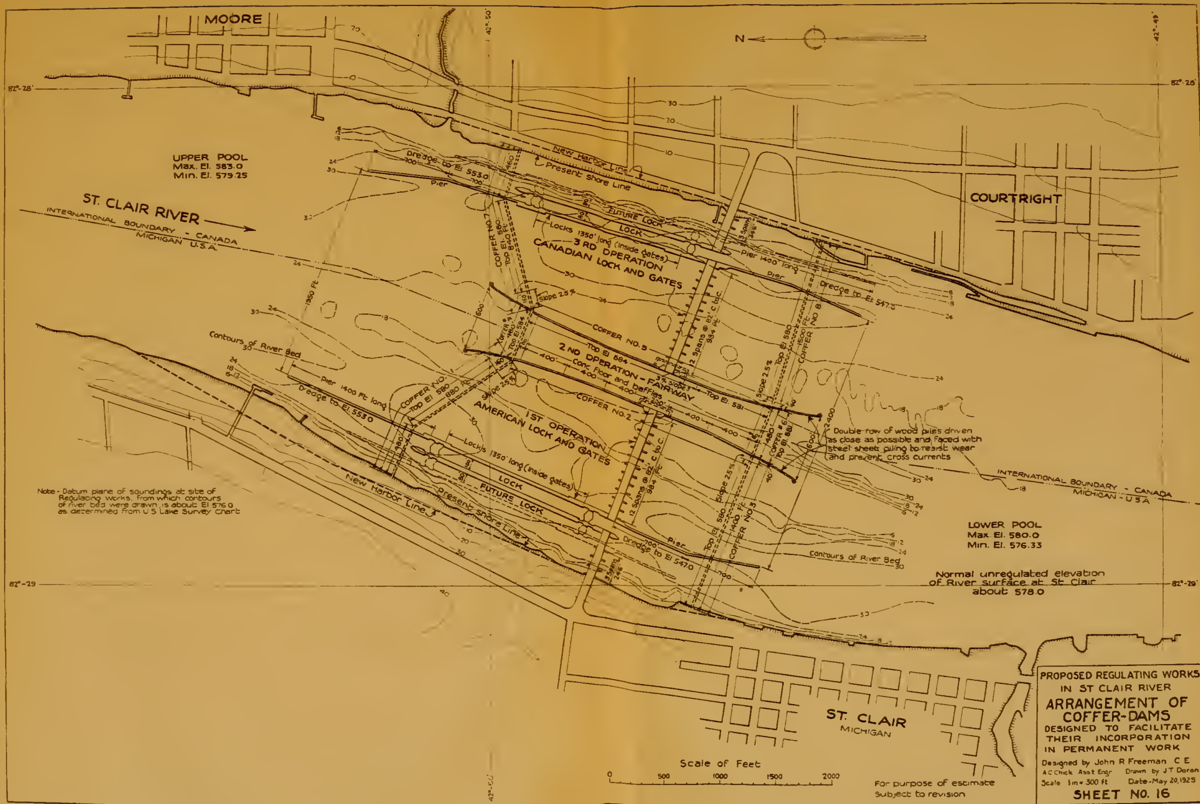
PROPOSED REGULATING WORKS
IN ST. CLAIR RIVER
LOCK DETAILS
DOWNSTREAM END
Designed by J.R. Freeman-Cons Engr
Drawn by J.T. Doran-Asst Engr
Date - May 20, 1926
Scale - 1 In. = 10 Ft
SHEET NO. 11



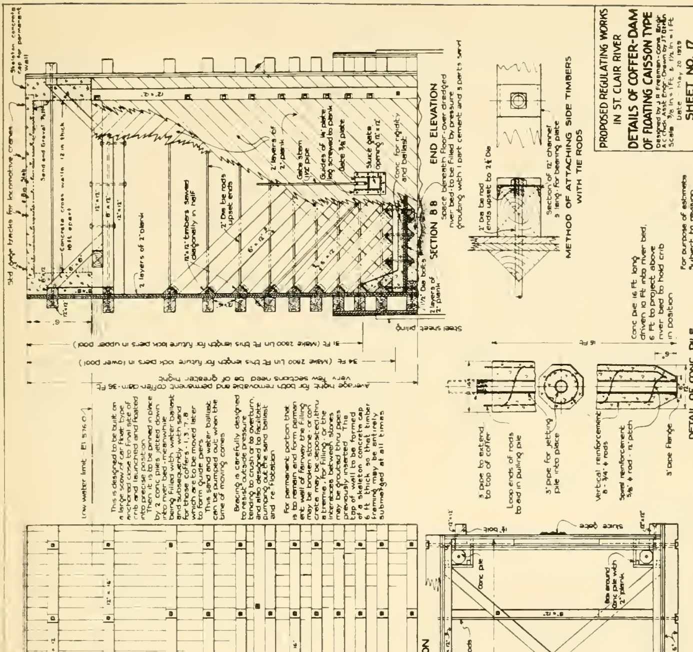
A special effort has been made in these designs to keep top of lock walls free of obstructions affecting clear view.
House over pump well
Recesses for egress of ice when opening gates
Cable passages
Pit for gate operating winch
Bollard
El 589.0
Upper pool
High water El 583.0
Electric winch for hoisting caterpillar gate
Seat for girder to support needle bars of temporary coffer dam
Electric capstan
El 584.0
Pump Ho Floor
Cyl. gate
Emptying culvert
30" Dia equalizing bypass
Gate vlv
Hoist well
Iron ladder in recess in wall
Openings into emptying culvert
Pump well 32'
Gate recess
Gate closed
Cable passages
Gate recess
Emergency gate recess
El 547.0
Caterpillar Gate
Debris pit
Debris pit
Debris pit
Passage
Pump well Floor
Drainage and equalizing culverts
Mitre walls
LONGITUDINAL SECTION ALONG CENTER LINE OF LOCK CHAMBER ON LINE M M
Bollard
High water
Cyl Gate
Emptying culvert
Emptying culvert
Drainage and equalizing culverts
SECTION N N
Conc counterweights for Cyl gates
Elec hoists for Cyl gates
Cylinder gates
H.W.
Cyl Gate 12'-6" Dia
Cyl Gate 12'-6" Dia
Emptying culvert
Hoist well
Emptying culverts
Passage
Drainage and equalizing culverts
SECTION P P
Stands for operating gate valves
Floor of pump Ho removable steel checker plates on I beams
PUMP HOUSE 42' x 28' Rein Conc roof on I beams Steel sash
Sluice gate hoist
High water
Motors directly connected by vertical shafts to pumps
10" gate vlv
48" Disch pipe
30" gate vlvs
Gate stem
30" Disch pipes
Emptying culvert
Cyl gate
12'-6" Dia
12' Dia
Check vlvs
4 x 7 sluice gates
10" Disch pipe
10" check Vlv
10" pump in sump
2 - 30" centrifugal pumps for pumping out locks for repairs
Drainage culverts
SECTION THRU PUMP WELL ON LINE Q Q
Scale of Feet
For purpose of estimate Subject to revision
PROPOSED REGULATING WORKS IN ST. CLAIR RIVER
LOCK DETAILS DOWNSTREAM END
Designed by J R Freeman - Cons Engr
Drawn by J T Doran - Asst Engr
Date - May 20 1925
Scale 1 In = 10 Ft
SHEET NO. 12


PROPOSED REGULATING WORKS
IN ST. CLAIR RIVER
STUDY FOR REGULATING GATES
WITH WIDE ARCHED BRIDGE
FOR HIGHWAY-WITH BASCULE
STEEL SPANS OVER LOCKS
AND DOUBLE BASCULE STEEL
SPAN OVER FAIRWAY.
Designed by John R Freeman-Cons. Engr.
A.C.chick-Ass't Engr. Drawn by J.T. Doran.
Scale-1 In.=6 Ft. Date-May 20, 1925.
SHEET NO. 13
ELEVATION LOOKING UPSTREAM
CROSS SECTION
AT PIER
AT CENTER OF SPAN
Scale of Feet
Also see sheet No. 14
For narrow arches intended for operating purposes and not for highway
But providing bases for piers of future high level steel truss highway bridge.
Estimates are based on sheet No. 15.
Note that one important purpose of these arches is to increase the stability of the slender piers between gates against possible ice pressures and excess water pressure when one gate is closed and the next gate wide open.
The head room is made ample for small boats or scows or tugs to pass beneath when a gate is wide open.
(As some will be most of the time in navigation season)
For details of Drop Gate and Hoist See Sheets No's 4, 5 and 6 Of Niagara River Studies
For purpose of estimate subject to revision.
Shaft hangers
1 5/16" Dia C R Shafting
Mitre gears
4" Dia hollow shaft.
Ladder
Spring line of arch
82' c. to c piers
Hoisting winch
El (586.5)
Clear span 76'
Top of gate when fully raised
Box girder
Pier 8'
15" I beams
C.I. lamp post
Trap door in floor over ladder
Resting seats
Electric conduits
Conc. pavement 8" thick
Possible future Electric Railway
Wood paving blocks
6" C.I. surface water drains - 2 in each pier
Earth or cinder Fill
Iron ladder
Broken stone drain
6" C.I drains - 3 in each pier
Spring line of arch
El. 586.5
Capstan
Bollard
Ladder
4" hollow shaft
Hoisting winch
Hoisting chain - End anchored securely into pier
El 582.6 - proposed Reg. high water, with 136,000 C.F.S - Huron at El. 583.5 - Erie at El 574.4
Max drop with Erie at 574.4 Huron at 583.5 - 136,000 CFS total flow (El 582.6)
Min Reg. L.W with Huron at El. 583.5 and Erie at El. 574.4
Normal unregulated water level - about El. 578.0
DIRECTION OF FLOW
(El 576.78)
Seat for girder to support needle bars of Tempy coffer dam.
15" I beams
Steel plate
El 567.0
Rolling sill of 15" steel pipe Filled with concrete
Rip rap 2' thick
Ribs 2' thick-12' apart
Space between ribs Filled with gravel
Minimum section
Steel sheet piling driven 15 or 20 Ft
Maximum section

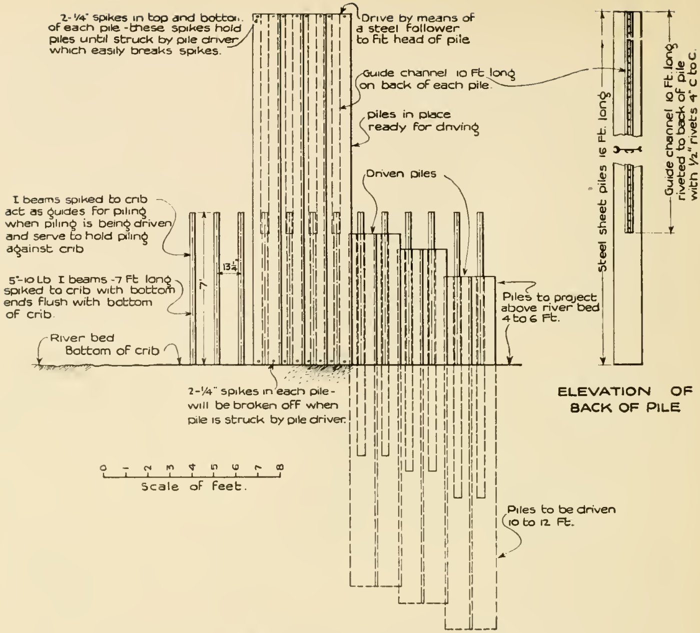

MICHIGAN - U S A
INTERNATIONAL BOUNDARY
CANADA
6% grade
Fairway
80 Lock
100 Lock
80' Lock
80' Lock
Length of approach about 1400 Ft
Length of approach about 1400 Ft.
3,444 Ft = 0.652 mile
ELEVATION LOOKING UPSTREAM
Scale - 1 In = 100 Ft.
Scale of Feet
Note: Loading - ordinary highway with single line of interurban Electric cars.
Note that because of possibility of indeterminate strains being introduced by a slight settlement of piers upon earth river bed. there must be no rigid continuity of truss over more than two supports
6% Grade
80' Future Lock
100' Lock
Reinf Conc arches for access to gates and winches - also for making rigid the narrow piers
Top of gates when fully raised
Passage
110' clear
Boats of 25' Max draft
Min clear depth
Top of conc baffles
River bed of sand and clay of indefinite depth
Steel sheet piling of depth as required
Fairway 350 Ft clear width (At narrowest section)
ELEVATION LOOKING UPSTREAM
Scale 1 In. = 50 Ft
Scale of Feet
Note: This is not a design, but an outline of overall dimensions - Truss forms and general details to be submitted by designer.
To be built when required upon supports to be now provided for in Regulation Works.
One controlling motive of design to be least practicable obstruction to view up and down river from approaching boats - and a general airiness of outline as seen from shores.
Roadway
Approx 120'
Adjustable "Drop Gate weir" for controlling river discharge
Conc base and gate sill
TYPICAL TRANSVERSE SECTION
Scale - 1 In = 50 Ft.
Anchor bolts
Conc. lining thick.
4" I beams riveted to shell
Butt joints with inner and outer butt straps double riveted
Steel shell 1" thick - riveted to base
Column to taper to 4' Dia at top
6' Dia
Conc lining
Cast steel base
anchor bolts
Provide hole for drainage
HORIZONTAL SECTION
VERTICAL SECTION
DETAIL OF COLUMN AND BASE
Scale 1/2 In. = 1 Ft
Scale of Feet
For purpose of estimate. Subject to revision
PROPOSED REGULATING WORKS IN ST. CLAIR RIVER
SKETCH SHOWING OUTLINES OF FUTURE HIGH BRIDGE
(About 12. miles downstream from Port Huron or at Foot of Lake St. Clair)
John R Freeman - Cons. Engr.
A C Chick Asst Engr Drawn by J T Doran
Scale - Various Date May 20, 1925
SHEET NO. 15



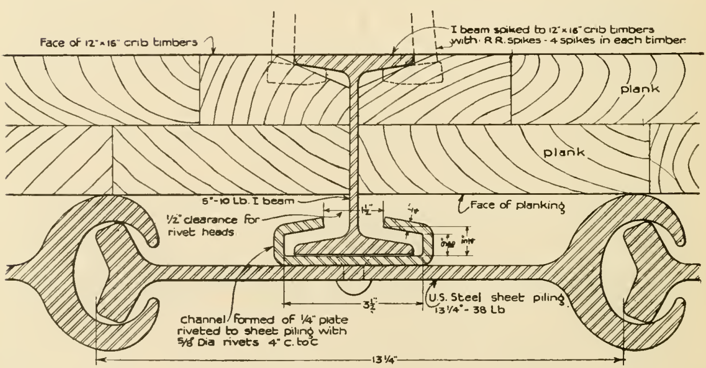
MOORE
COURTRIGHT
ST. CLAIR
MICHIGAN
N
ST. CLAIR RIVER
INTERNATIONAL BOUNDARY - CANADA
MICHIGAN U.S.A.
UPPER POOL
Max. El. 583.0
Min. El. 579.25
LOWER POOL
Max. El. 580.0
Min. El. 576.33
3 RD OPERATION
CANADIAN LOCK AND GATES
2 ND OPERATION - FAIRWAY
1 ST OPERATION
AMERICAN LOCK AND GATES
New Harbor Line
Present Shore Line
FUTURE LOCK
LOCK
Locks 1350' long (inside gates)
COFFER NO. 5
COFFER NO. 2
Contours of River Bed
Dredge to El. 553.0
Dredge to El. 547.0
Pier 1400 Ft. long
Double row of wood piles driven as close as possible and faced with steel sheet piling to resist wear and prevent cross currents
Normal unregulated elevation of River surface at St. Clair about 578.0
Note - Datum plane of soundings at site of Regulating Works, from which contours of river bed were drawn, is about El. 576.0 as determined from U.S. Lake Survey Chart
Scale of Feet
0 500 1000 1500 2000
For purpose of estimate
Subject to revision
PROPOSED REGULATING WORKS
IN ST CLAIR RIVER
ARRANGEMENT OF COFFER-DAMS
DESIGNED TO FACILITATE THEIR INCORPORATION IN PERMANENT WORK
Designed by John R Freeman C E
Drawn by J T Doran
Date - May 20, 1925
SHEET NO. 16



DETAILS OF COFFER-DAM OF FLOATING CAISSON
TYPE FOR ST. CLAIR RIVER



ELEVATION OF SIDE OF CRIB
SHOWING STEEL SHEET PILING



DETAIL OF SHEET PILING AND GUIDING DEVICE

Scale of inches.

METHOD OF DRIVING STEEL SHEET PILING IN CLOSE CONTACT WITH EDGE OF COFFER-DAM

ESTIMATE OF QUANTITIES AND COSTS FOR ST. CLAIR REGULATING WORKS

COFFER-DAMS — PERMANENT TYPE

Permanent type coffer-dam to form side walls of fairway. Total length 4,240 feet	Quantity	Unit Cost in Place	Total Cost per Section 41 ft. long	Total Cost
Lumber—Heavy framing and miscl. pcs.	45,100 bd. ft.	$100.00 per M	$4,510	
Planking	26,350 bd. ft.	80.00 per M	2,108	
Bolts, tie wds., nuts, washers, etc.	29,380 lbs.	.08	2,350	
Construction Railroad—Rails	1,915 lbs.	.05	95	
Accessories	270 lbs.	.06	16	
Steel Sheet Piling	45,100 lbs.	.07	3,157	
I-beams and guide channels for piles	9,624 lbs.	.07	675	
Concrete cap skeleton 1-2-4 mixture				
Concrete	67 c.y.	15.00	1,005	
Gravel	117 c.y.	2.50	295	
Pressure grouting beneath coffer				
3 inch pipe	108 ft.	.75	80	
Concrete—1-10 mixture	15 c.y.	15.00	225	
Broken stone fill	750 c.y.	2.00	1,500	
2 concrete piles 14″ x 14″ x 16 ft. long	1.6 c.y.	50.00	80	
Slide gate on each end of coffer with stem	400 lbs.	.10	40	
Total cost per 41 ft. section			16,166	
Total cost per lineal foot		395.00		
Total cost for 4,240 lineal feet				$1,675,000
Excavation for coffer dam forming walls of fairway—Dredging	47,400 c.y.	1.00		47,400
Extra and Alternative				
A. Concrete grouting interior of coffer-dam allowing 45 per cent voids	338 c.y.	18.00	6,084	
Cost per lineal ft.		149.00		
Cost for 4,240 ft.				632,000
B. Concreting entire inside volume of coffer section, instead of filling with stone, not including 6 ft. thick concrete cap	750 c.y.	15.00	11,250	
Cost per lineal foot		275.00		
Cost per 4,240 feet				1,167,000
(Deduct for stone fill above)				155,500
				$1,011,500

COFFER-DAMS — REMOVABLE TYPE

Removable type coffer-dam—to be used as pier walls for locks after construction of regulating works is complete. Total length 7,520 feet	Quantity	Unit Cost in Place	Total Cost per Section 41 ft. long	Total Cost
Lumber—Frame and misc. pcs.	45,100 bd. ft.	$100.00 per M	$4,510	
Planking	26,350 bd. ft.	80.00 per M	2,108	
Bolts, tie rods, nuts, washers, etc.	29,380 lbs.	.08	2,350	
Construction Railroad—Rails	1,915 lbs.	.05	95	
Accessories	270 lbs.	.06	16	
Steel sheet piling	45,100 lbs.	.07	3,157	
I-beams and guide channels for piles	9,624 lbs.	.07	675	
Pressure grouting beneath coffer 3 inch pipes	108 ft.	.75	80	
Concrete 1-10 mixture	15 c.y.	15.00	225	
Sand and gravel fill	896 c.y.	2.00	1,792	
2 concrete piles	1.6 c.y.	50.00	80	
Slide gate and stem each end of coffer	400 lbs.	.10	40	
Total cost per 41 ft. section			15,128	
Total cost per lineal foot		369.00		
Total cost for 7,520 feet				$2,775,000
Pumping out area within coffer-dam				
Total number of gallons	2,030,000,000			
Average height of lift 15 ft. at unit cost of 60 cents per million foot-gallons			18,270	18,270
Leakage and continuous pumping 2-6 inch pumps continuously for 3 years at $20 per day			21,900	21,900
				$2,815,170

FAIRWAY

Fairway	Quantity	Unit Cost in Place	Total Cost	Total Cost
Excavation for bottom,	271,500 c.y.	$ .50	$135,750	
Floor of Fairway concrete 1-3-6	9,950 c.y.	20.00	199.000	
Concrete baffles	8,750 c.y.	25.00	218,750	
Weepers	45 c.y.	25.00	1,125	
Reinforcement for bottom of Fairway	250 tons	100.00	25,000	
Pile walls extending 500 ft. at each end of fairway	3,200 piles	45.00	144,000	
Steel sheet piling for facing pile wall	1,550 tons	150.00	232,500	
Concrete piers at ends of arch bridge for support of future steel bridge				
Concrete	13,520 c.y.	15.00	202,700	
Steel sheet piling	65 tons	150.00	9,750	
			$1,168,575	$1,168,575

NARROW CONCRETE SPAN FOR BRIDGE AND GATES

	Quantity per Span	Unit Cost	Cost per Span	Cost per 30 Spans
Concrete in bridge and piers:				
Superstructure incl. road surfaces	340 c.y.	$25.00	$8,500	$255,000
Piers (concrete)	1,225 c.y.	20.00	24,500	735,000
Dam and foundation for gates	725 c.y.	20.00	14,500	435,000
Gravel fill for above	455 c.y.	1.00	455	13,650
Reinforcement for bridge	20 tons	100.00	2,000	60,000
Steel sheet piling	87 tons	200.00	17,400	522,000
Earth fill for arch spandrels (tamped)	380 c.y.	3.00	1,140	34,200
Rock fill for drains at piers	8 c.y.	3.00	24	720
Drain pipe 6 inches cast iron	400 lbs.	.03	12	360
Drop steel gates	60.5 tons	200.00	12,100	363,000
Bearing blocks for gates	6,000 lbs	.07	420	12,600
Hoisting gear with motor	1	5,250.00	5,250	157,500
Hoisting chain	8,740 lbs.	.25	2,190	65,700
Shifting including bearings, etc., from one pier to other end of gate			400	12,000
Bearing plates for needle bars	13,600 lbs.	.06	816	24,480
Lamp posts	1	50.00	50	1,500
Electric conduit tile —	250 ft.	.05	13	390
Trap doors	1	10.00	10	300
Iron ladder downstream side only	1	100.00	100	3,000
Ring bolts	4	5.00	20	600
Bollards	2	75.00	150	4,500
Geared capstan	1	300.00	300	9,000
Claw hooks	2	25.00	50	1,500
Guard chain 100 ft. long 2½ in. dia.	2,500 lbs.	.10	250	7,500
Excavation	57,000	.50		28,500
				$2,748,000

80 FOOT LOCK-CANADIAN SIDE

	Quantity	Unit Cost in Place	Total Cost	Total Cost
Excavation, earth	270,000 c.y.	$ .50	$135,000	
Plain concrete 1-3-6 mixture	124,140 c.y.	15.00	1,862,000	
Reinf. concrete 1-2-4 mixture	123,572 c.y.	20.00	2,471,440	
Reinf. concrete nozzle wall 1-2-4 mixture	240 c.y.	30.00	7,200	
				$4,475,640
Reinforcement 50 lbs. / c.y. or 38%	3,100 tons	100.00	310,000	310,000
Lock gates—8 leaves	1,240 tons	200.00	248,000	
Anchorages, reaction castings, etc.	174 tons	200.00	34,800	
Timber fenders	25 M bd. ft.	80.00	2,000	
Cables, winches, etc. for gates	8 sets	3,625.00	30,000	
				314,800
Geared capstans with motors	4	500.00	2,000	
Bollards	16	50.00	800	
				2,800
Caterpiller gates—settings and hoists	4	6,000.00	24,000	24,000
Trash racks 36 ft. x 26 ft. wide	4	4,000.00	16,000	16,000
Cylinder gates 15 ft. high	3	1,200.00	3,600	
Cylinder gates 21 ft. high	1	1,500.00	1,500	
Cylinder gates Hoists	4	500.00	2,000	
Concrete counter balances	9 c.y.	25.00	225	
				7,325
Motor driven centrifugal pump in well —12 in. suction and discharge	1 unit	3,500.00	3,500	
12 in. pipe and values			895	
Pump room—structure			3,000	
2 motors and 2—30 in. pumps	2 units	10,000.00	20,000	
1 motor and 10 in. pump	1 unit	3,000.00	3,000	
48 in. pipe	3,800 lbs.	.10	380	
30 in. pipe	23,418 lbs.	.10	2,340	
30 in. values (2 check, 2 gate)	4		5,400	
10 in. pipe	2,625 lbs.	.10	265	
10 in. values	2		265	
2—4 ft. x 7 ft. sluice gates, stems and stands	2 units	1,500.00	3,000	
				42,045
Guard rails	700 ft.	.40	280	
Checkered plate ⅜ in. 4,320 sq. ft.	70,500 lbs.	.07	4,935	
Iron ladders in lockwall recess	2	50.00	100	
				5,315
Operating tower and equipment	2	20,000.00	40,000	40,000
Bulkheads for caterpillar and cylinder gate openings for future lock concrete	100 c.y.	20.00	2,000	2,000
				$5,239,925

PIER WALLS FOR LOCKS

Total Length 5,400 ft. made up of salvaged coffer-dam sections

	Quantity	Unit Cost in Place	Total Cost	Total Cost
Pumping out gravel and sand	896 c.y.	$ .50	448	
Floating and towing into new position			100	
Pulling concrete piles and rejetting			50	
Filling with crushed and broken stone	750 c.y.	2.00	1,500	
Grouting under coffer 1-10 mixture	15 c.y.	15.00	225	
Concrete cap 6 ft. thick	183 c.y.	15.00	2,745	
Total cost per 41 ft. section			$5,068	
Total cost per foot length		124.00		
Total cost for 5,400 feet				$670,000
Excavation upstream and downstream approaches to locks—dredging	100,800 c.y.	.50	100,800	
Excavation to New Harbor lines	935,000 c.y.	.75	700,100	
				800,900
High Steel bridge:				
Superstructure 3,444 ft. long			2,000,000	
Steel work for approaches, total 2,800 ft. long			900,000	
Foundations for approaches			100,000	
				3,000,000
				$4,470,900

100 FOOT LOCK-AMERICAN SIDE

	Quantity	Unit Cost in Place	Total Cost	Total Cost
Excavation, earth	310,000 c.y.	$ .50	$155,000	
Plain concrete 1-3-6 mixture	138,000 c.y.	15.00	2,072,500	
Reinf. concrete 1-2-4 mixture	140,465 c.y.	20.00	2,809,300	
Reinf. concrete nozzle wall 1-2-4 mixture	293 c.y.	30.00	8,790	$5,045,590
Reinforcement 38 per cent	3,520 tons	100.00	352,000	352,000
Lock gates—8 leaves	1,506 tons	200.00	301,200	
Ancorages, reaction, castings	212 tons	200.00	42,400	
Timber finders	25 M bd. ft.	80.00	2,000	345,600
Cables, winches, etc. for lock gates	8 sets	3,750.00	30,000	
Geared capstans with motors	4	500.00	2,000	
Bollards	16	50.00	800	32,800
Caterpillar gates—setting and hoists and trash racks 36 ft. x 26 ft., etc	4	4,000.00	16,000	16,000
Cylinder gates 15 ft. high	3	1,200.00	3,600	
Cylinder gates 21 ft. high	1	1,500.00	1,500	
Cylinder gates—Hoists	4	500.00	2,000	
Concrete counter balances	9 c.y.	25.00	225	7,325
Motor driven centrifugal pump in well —12 in. suction and discharge	1 unit	3,500.00	3,500	
12 in. pipe—gates and check valves complete			898	
1 pump room—structure			3,000	
2—30 in. pumps with motors	2 units	10,000.00	20,000	
1—10 in. pump with motors	1 unit	3,000.00	3,000	
48 in. pipe	3,800 lbs.	.10	380	
30 in. pipe	23,418 lbs.	.10	2,340	
30 in. valves	4		5,400	
10 in. pipe	2,625 lbs.	.10	265	
10 in. values	2		265	
4 ft. x 7 ft. sluice gates with stems and stands	2 units	1,500.00	3,000	42,045
Guard rails	700 ft.	40.00	280	
Checkered plate 3/8 in.—4,320 sq. ft.	70,500 lbs.	.07	4,935	
Iron ladders in lock wall recesses	2	50.00	100	5,315
Operating tower and equipment	2	20,000.00	40,000	40,000
Bulkheads for caterpillar and cylinder—gates openings for future lock —concrete	100 c.y.	20.00	2,000	2,000
				$5,888,675

SUMMARY OF COST ESTIMATE

St. Clair Locks and Regulation Works

Permanent type coffer-dam for walls of fairway		$1,675,000
(a) for grouting interior of coffer filled with stone add	$632,000	
(b) for filling coffer with concrete instead of stone and grouting add	1,011,500	
Excavation for permanent coffer-dam		47,400
Removable type coffer-dam		2,815,170
Unwatering coffer-dam		18,270
Pumping during construction		21,900
Fairway construction		1,168,575
Narrow concrete bridge with regulating gates		2,748,000
80 ft. lock Canadian side of river		5,239,925
100 ft. lock American side of river		5,888,675
Pier walls for locks (salvaged coffer-dam sections reset and capped with concrete after filling with stone		670,000
Excavation, approaches to locks		100,800
Excavation to new harbor lines		700,100
		$21,093,875
If fairway walls are pressure grouted add (a)	632,000	
If fairway walls are concrete filled add (b)	1,011,500	
Add for engineering supervision contingencies and minor omissions, 20 per cent		4,218,775
	Total	$25,312,650

ALTERNATIVE WIDE BRIDGE SPAN AND GATES
(Not Recommended. Propose Future High Steel Bridge)

	Quantity per Span	Unit Cost	Cost per Span	Cost per 30 Spans
Concrete in bridge and piers:				
Superstructure, incl. road surfaces	900 cu. yd.	$25.00	$22,500	$675,000
Piers (average) 26 full piers and 8 half piers equal 30 piers	2,060 cu. yd.	20.00	41,200	1,236,000
Dam and foundation for gates (aver.)	725 cu. yd.	20.00	14,500	435,000
Gravel fill	455 cu. yd.	1.00	455	13,650
Reinforcement	50 tons	100.00	5,000	150,000
Steel sheet piling 20 ft. long	124 tons	200.00	24,800	744,000
Wood block paving for roadway	200 sq. yd.	3.00	600	18,000
Earth fill for spandrels of arches	1,400 cu. yd.	3.00	4,200	126,000
Rock fill for drains at piers	30 cu. yd.	3.00	90	2,700
Drain pipe 6 inch cast iron	1,080 lbs.	.03	35	1,050
Steel drop gates	60.5 tons	200.00	12,100	363,000
Bearing blocks for gates	6,000 lbs.	.07	420	12,600
Hoisting gear with motor	1	5,250.00	5,250	157,500
Hoisting chains	8,740 lbs.	25.00	2,190	65,700
Shafting incl. bearings, etc. from one pier to other end of gate:			400	12,000
Bearing plates for needle bars	13,600 lbs.	.06	816	24,480
Lamp posts	2	50.00	100	3,000
Electric conduit—tile	500ft.	.05	25	750
Trap doors	2	10.00	20	600
Iron ladders—upstream side	1	50.00	50	1,500
Iron ladders—downstream side	1	100.00	100	3,000
Ring bolts	7	5.00	35	1,050
Bollards	2	75.00	150	4,500
Capstans geared	1	300.00	300	9,000
Claw hooks	2	25.00	50	1,500
Guard chain 100 ft. long 1½in. dia.	2,500 lbs.	10.00	250	7,500
Excavation	87,300 cu. yd.	.50		43,650
				$4,112,130

Estimated cost of narrow bridge and shorter piers 2,748,000

Excess of cost for wide low concrete bridge $1,364,130

This if saved can go toward cost of a high steel truss bridge carried on concrete piers between sluice gates. The steel superstructure is estimated to cost $2,000,000

Cost of steel bridge is not included in present estimate. This is not needed as part of present project, and can be added at any future time.

REGULATING EFFECT OF WORKS PROPOSED

Method of Estimating Increase in Depth for Navigation and Increase of Minimum Flow of Water for Power.

Early in this investigation it was found that the limits to regulation of both elevation and discharge were set by natural conditions and not by structural possibilities; that the structures might be designed at first to cover the maximum range ultimately possible and operated within smaller limits until the time should come for maximum use, all with greater economy than to build now of smaller scope and at some future time enlarge the range in height of regulation.

The maximum limit of elevation appears set by the high water of 1838, recorded on all of the charts; and the low limit is set by the minimum depth of draft to which the great ore boats can be loaded without serious loss.

As to regulating the discharge, the first requirement of the early years after completing the works is to hold back the discharge to the greatest permissible extent all along the line, from Lake Superior to Lake Erie inclusive, until the lakes are refilled and the former high working levels are restored; making this accumulation largely in the non-navigation, winter season. In the case of Niagara Falls, water may be held back also at night until the elevation of Lake Erie is restored, leaving, however, always a reasonable minimum over the Falls at night after supplying the needs for power.

With high lake levels once restored, thenceforth a systematic program would be followed, designed to divide the benefits of regulation between high levels for navigation, and the maintenance of a more uniform flow, by storing water in years of large rainfall, or years of small evaporation, for use in times of scarcity.

It has appeared logical to first describe the proposed regulation works as designed for maximum control, and then to show how they could be made most useful, and their benefits equitably divided between navigation, power, and improvement of scenic effect at Niagara Falls.

Obviously, in early years the works can be tested out over a narrower range than it is expected to use years hence, after larger development of power. As to the elevation to which each of the lakes can be regulated for the greatest good to the greatest number, the **entire limit of debatable ground is at most a matter of only a few inches, and if flowage height must be lowered recourse can be had to dredging.**

The allowable range between high water and low water has been discussed on a previous page. Also the natural changes in lake elevation.

The next, and the most important, of the hydraulic questions to be considered in deciding just how these works are to be used for regulating both lake heights and increase of minimum discharge for use of power with maximum benefit to the public, are

(1) How large is the natural water yield of each lake?

(2) How much does it vary from year to year and from month to month?

(3) How large is the reservoir capacity of each lake between available limits of elevation for high and low water?

The record of discharge of the Niagara River is of first importance, because here the chief adjustments will be made from day to day, and sometimes from hour to hour, and because the Niagara discharge is the sum of the net yields of all of the Great Lakes drainage areas, from Superior to Erie.

A study of the addition to the St. Lawrence discharge from the added storage in Lake Ontario is postponed, awaiting the development of plans for improving the St. Lawrence, by the Internatianal Commission.

NEED OF GREATER ACCURACY IN THE WINTER RECORD OF DISCHARGE

All through the estimates of water yield from each lake, illustrated in the tables on page 49, and in the computation of mass curves on later pages, it will be found that lack of more exact information has compelled the use of the same somewhat uncertain value as a correction to allow for the retarding effect of ice when a formula determined in summer is used for estimating the winter discharge. It is well known that this ice effect varies greatly in different years and that the values one is compelled to use for lack of something better are merely a sort of guess "tempered" with judgment. There is no real need for this, and **with the resources of two great and prosperous countries joined in the important problems of these great rivers, absence of exact information ought not to continue.**

It would be neither expensive or difficult to maintain a daily measurement for an hour each day from the International bridge across the Niagara River, dropping a warm current meter with electric transmission register into the middle of representative spans at a few feet below surface and determine the velocity at a fixed station to which a coefficient could be applied, and if a meter was occasionally bruised by ice, and sometimes lost the cost would not be excessive in relation to value of accurate information. A particularly strong current meter could be devised.

In the narrow deep gorge at the head of the St. Clair River which always remains open, means also could be devised in several different ways, for a daily measurement in mid-channel to which a coefficient could be applied.

COMPARISON OF THE VARIOUS RECORDS OF DISCHARGE

There have been published from time to time during the past 25 years, as per schedule below, various tables of average monthly discharge of Lake Erie, each derived by slightly differing formulas for discharge as computed from elevation of Lake Erie.

A.—U. S. Chief Engineers Report . . .	1902—p. 2838—	Monthly Averages	Apr. 1899 to Mar. 1902 inc.
B.—U. S. Chief Engineers Report . . .	1903—p. 2875—	Monthly Averages	Jan. 1860 to Dec. 1902 inc.
C.—International Waterways Commission Regulating Lake Erie including canal diversions	1910—p. 81—	Monthly Averages	Jan. 1860 to Dec. 1907 inc.
D.—International Waterways Commission Regulating Lake Erie excluding diversions	1910—p. 136—	Monthly Averages	Jan. 1890 to Dec. 1906 inc.
E.—Transcript U. S. Supreme Court Vol. VII Gardiner S. Williams	1923—p. 373–4—	Monthly Averages	Jan. 1900 to Dec. 1907 inc.
F.—U. S. Lake Survey Office Blue Print Tables	1924—1925—	Monthly Averages	Jan. 1899 to Dec. 1924 inc.
G.—F. C. Shenehon (Green Book) Regulation of Niagara and St. Lawrence	1919—p. 35–41–	Monthly Averages	Jan. 1893 to Dec. 1902 inc. Jan. 1907 to Dec. 1916 inc.
H.—F. C. Shenehon A. S. C. E. Tran. paper on St. L. Waterway St. Lawerence yield only	1925—p. 1277—	Yearly Averages	1891–4 to 1925–4

These values differ slightly, therefore the monthly or yearly average discharges were all arranged in parallel columns and their differences analyzed, with the result of finding that when allowances had been made for diversions by Chicago, Welland and Erie Canals, and for retardation of discharge by ice, and for rise or fall of surface, some of which compensations had been applied in certain series and not in others, all were substantially the same, within a small percentage, which is inside the limits of precision of measurement; and that these differences are of no importance in the present problems.

For example, the values of average monthly discharge given by tables received from the Lake Survey office at Detroit in 1924, agree within one per cent of the values published in the Chief of Engineers report of 1902, notwithstanding all of the measurements, and discussions of formulas, in the intervening 22 years. Thus the earliest and the latest in the above schedule of tables of discharge, are in substantial agreement.

A review of the history of the measurements of height and quantity given in brief in Appendix No. 1, gave satisfactory proof of the accuracy of these measurements.

A table which follows on a later page illustrates how small is the amount of divergence found between the different published estimates of the average monthly rate of discharge of the Niagara River.

Only the three years 1899, 1900 and 1901 are included in this comparison, because these appear sufficient for the present purpose of illustrating that the differences between estimates by different formulas and by different computers have been small. This particular group of three years was selected for illustration because in the year 1900 the St. Clair River was remarkably free from obstruction by ice; while in the year 1901 the obstructions by ice were the most severe found in the records, with the exception of 1918. It may be assumed that these same general conditions found in the St. Clair River respecting ice also prevailed along the upper Niagara River.

The standard for comparison in measuring the percentages of difference noted in this table, is the estimate presented in blue print table furnished by the U. S. Lake Survey Office on March 9, 1925, and from which the column marked (E) in the following table of comparisons was copied. The writer is informed that the Lake Survey office did not carry the revision of estimates back further than 1899 because of doubts if precision of the observations warranted so doing. Retardation by ice is the chief cause of uncertainty.

These values for discharge are obtained by means of diagram or formula from the average of the recorded elevations of Lake Erie as observed at the Buffalo breakwater. In one series (B), the elevation of Lake Erie given by the Cleveland gauge was used. No reason appears for the excess found by these Cleveland values.

COMPARISON OF ANNUAL AVERAGES

The first table of comparisons relates to monthly averages and serves to show there was no important difference between the results of the various revisions of formulas made during the past 25 years, from month to month or from summer to winter, and that all of these published estimates have not included a correction for the clogging of the lake outlets by ice, but have applied formulas derived from gaggings made in summer, to the recorded observations made in winter on elevations of lakes, for deriving the discharge in winter months.

The second table of comparisons is between the 5-year averages of discharge for each lake as published by various authorities. Some of which include compensation for storage or release, in rise or fall of lake levels, but none of which are found to contain correction for ice.

No allowance for change in relation at the outlet of Lake Huron before and after the year 1890 appears in any of these estimates (see pages 404 to 410).

COMPARISON OF VARIOUS PUBLISHED VALUES FOR AVERAGE MONTHLY DISCHARGE OF NIAGARA RIVER

		A		B		C		E	D	
		From Report of Chief of Engineers, U. S. Army, 1902, page 2838 from Buffalo gage.		From Report of Chief of Engineers, U. S. Army, 1903, pages 2875–76, from Cleveland gage		From Report of International Waterways Commission, 1910, pages 139–140, Table 33 (Haskell estimates) Values are as measured without allowance for diversions upstream.		The values below are taken as standard for comparison. From blueprint table supplied by U. S. Lake Survey Office, Sherman Moore, Assistant Engineer.	From Testimony G. S. Williams 1913, vol. VII, page 373, Table XI, (Computed by formula from record of elevations observed at bridge section).	
Date Year and Month	Mean Monthly Elevation of Lake Erie at Buffalo feet	Discharge in cubic feet per second	Per Cent variation from latest estimate from U.S.L.S. office	Discharge in cubic feet per second	Per Cent variation from latest estimate from U.S.L.S. office	Discharge in cubic feet per second	Per Cent variation from latest estimate from U.S.L.S. office	Discharge in Cubic Feet per second	Discharge in cubic feet per second	Per Cent variation from latest estimate from U.S.L.S. office
1899										
Jan.	572.05	—	—	198,033	+2.87	195,300	+1.45	192,500	—	—
Feb.	571.59	—	—	193,316	+2.99	185,400	—1.24	187,700	—	—
Mar.	571.85	—	—	201,628	+4.31	190,800	—1.31	193,300	—	—
Apr.	572.04	197,000	—0.15	208,366	+5.61	195,200	—1.06	197,300	—	—
May	572.32	202,800	—0.35	215,329	+5.81	201,500	—0.98	203,500	—	—
June	572.51	207,500	—0.05	218,024	+5.02	205,800	—0.87	207,600	—	—
July	572.45	206,200	—0.05	211,735	+2.63	204,500	—0.87	206,300	—	—
Aug.	572.09	198,000	—0.25	207,467	+4.51	196,200	—1.16	198,500	—	—
Sept.	571.90	193,800	—0.26	202,076	+4.00	192,000	—1.18	194,300	—	—
Oct.	571.48	185,000	—0.16	196,685	+6.14	182,900	—1.30	185,300	—	—
Nov.	571.55	186,500	—0.16	196,910	+5.42	184,500	—1.23	186,800	—	—
Dec.	571.96	195,000	—0.36	190,621	—2.59*	193,300	—1.23	195,700	—	—
Mean	571.98	—	—	203,350	+3.90	194,000	—0.91	195,700	—	—
1900										
Jan.	571.67	189,300	0.00	191,070	+0.93	187,000	—1.21	189,300	189,675	+0.20
Feb.	571.61	187,800	—0.16	195,787	+4.03	185,700	—1.28	188,100	188,360	+0.14
Mar.	571.82	192,200	—0.21	203,649	+5.73	190,200	—1.24	192,600	192,960	+0.19
Apr.	572.16	199,700	—0.05	210,612	+5.41	197,800	—1.00	199,800	200,405	+0.32
May	572.33	203,700	0.00	214,206	+5.16	201,700	—0.98	203,700	204,130	+0.21
June	572.41	205,000	—0.19	216,003	+5.16	203,500	—0.93	205,400	205,880	+0.23
July	572.43	205,800	0.00	213,083	+3.54	204,000	—0.87	205,800	206,520	+0.35
Aug.	572.31	202,600	—0.29	212,409	+4.52	201,300	—0.93	203,200	203,690	+0.24
Sept.	572.07	197,800	—0.10	205,221	+3.65	195,700	—1.16	198,000	198,430	+0.22
Oct.	571.68	189,500	—0.05	199,830	+5.39	187,200	—1.26	189,600	189,890	+0.15
Nov.	571.84	192,700	—0.15	193,990	+0.52	190,600	—1.24	193,000	193,400	+0.21
Dec.	571.77	191,600	+0.05	193,091	+0.79	189,100	—1.25	191,500	191,865	+0.19
Mean	572.01	196,500	—0.10	204,079	+3.74	194,500	—1.11	196,700	197,090	+0.22
1901										
Jan.	571.60	190,700	+4.43	190,845	+4.51	185,500	+1.59	182,600	188,140	+3.03
Feb.	571.03	173,800	—0.80	182,984	+4.44	173,400	—1.03	175,200	175,655	+0.26
Mar.	570.82	170,900	—0.18	180,288	+5.30	169,100	—1.22	171,200	171,105	—0.05
Apr.	571.05	175,800	—0.23	189,498	+7.55	173,900	—1.30	176.200	176,095	—0.06
May	571.17	178,500	—0.17	199,156	+11.38*	176,500	—1.29	178,800	178,725	—0.04
June	571.69	189,400	—0.21	203,424	+7.18	187,500	—1.21	189,800	190,110	+0.16
July	571.88	193,500	—0.16	203,424	+4.96	191,500	—1.19	193,800	194,270	+0.24
Aug.	571.70	189,600	—0.21	200,504	+5.53	187,600	—1.26	190,000	190,330	+0.17
Sept.	571.75	190,700	—0.26	198,932	+4.04	188,700	—1.31	191,200	191,425	+0.12
Oct.	571.53	186,100	—0.16	190,396	+2.15	184,000	—1.29	186,400	186,605	+0.11
Nov.	571.39	183,000	—0.16	186,577	+1.79	181,000	—1.25	183,300	183,540	+0.13
Dec.	571.39	182,700	—0.16	187,215	+2.30	180,600	—1.31	183,000	183,100	+0.05
Mean	571.42	183,700	+ .14	192,770	+5.09	181,600	—1.01	183,500	184,200	+0.34

*Extreme variations.

LONG TERM COMPARISONS OF ESTIMATES OF TOTAL WATER YIELD OF LAKES SUPERIOR, MICHIGAN, HURON AND ERIE AS MEASURED AT HEAD OF NIAGARA RIVER

	Without adjustment for changes in elevations of four lakes from year to year			With adjustment for changes in elevations of four lakes from year to year	
	Values as printed in Report on Regulation of Lake Erie by Int. Waterways Commission in 1910, combined into five-year periods. The values below include additions of 1000 c.f.s. for flow through Erie Canal and 1100 c.f.s. for flow through Welland Canal. No addition has been made for the diversion at Chicago since 1900. No correction has been made for retardation of flow due to ice.	From tables supplied by U. S. L. S. office, dated May 1924. Discharge computed from Lake elevation by formula. $Q=3904$ (Buffalo Gauge $-558.37)^{\frac{3}{2}}$ "Flow through Erie and Welland Canal is not included." "No correction has been made for retardation of flow due to ice in winter months."	Values as computed by A. C. Chick. Using values for Niagara Discharge from 1860 to 1907 inclusive as given in Report on Regulation of Lake Erie — 1910, page 81; and from 1908 to 1924 inclusive, values given in blue-print tables furnished by U. S. L. S. office. Additions have been made for measured diversions through Erie and Welland Canals and, since 1900, through Chicago Drainage Canal. Deductions of 6000 c.f.s. for Jan. and 9000 c.f.s. for Feb. have been made for retardation of flow due to ice in Niagara River.	From Mr. F. C. Shenehon's paper before the A. S. C. E., Oct. 23, 1924. These values include additions for the volume of flow passing through Erie and Welland Canals and the volume passing through Welland Canal for water-power uses, also the outflow since 1900 through the Chicago Drainage Canal are counted as outflowing through the Niagara River. A deduction for ice of 6000 c.f.s. for Jan. and 9000 c.f.s. for Feb. has been made.	Values as computed by A. C. Chick. Using values for Niagara Discharge from 1860 to 1907, inclusive, as given in Report on Regulation of Lake Erie — 1910, page 81; and from 1908 to 1924, inclusive, values given in blue-print tables furnished by U. S. L. S. office. Additions have been made for measured diversions through Erie and Welland Canals, and, since 1900, through Chicago Drainage Canal. Deductions of 6000 c.f.s. for Jan. and 9000 c.f.s. for Feb. have been made for retardation of flow due to ice in Niagara River.
Period	C.F.S.	C.F.S.	C.F.S.	C.F.S.	C.F.S.
1860–1864	231,000	——*	228,630	202,000	208,700
1865–1869	209,400	——	207,110	213,000	215,100
1870–1874	212,300	——	209,950	202,000	207,800
1875–1879	219,800	——	217,430	206,000	208,200
1880–1884	223,600	——	221,830	234,000	238,600
1885–1889	221,000	——	219,750	210,000	205,300
Mean 30 years	219,500	——	217,450	211,200	214,000
1890–1894	206,100	——	204,730	186,000 (1891–1895)†	205,200
1895–1899	191,500	——	190,590	211,000 (1896–1900)	189,000
1900–1904	197,900	197,500	202,190	210,000 (1901–1905)	207,400
1905–1909	——*	206,800	213,850	198,000 (1906–1910)	207,500
1910–1914	——	198,100	208,610	218,000 (1911–1915)	202,600
1915–1919	——	203,500	215,730	215,000 (1916–1920)	222,200
1920–1924	——	191,900	204,170	175,000 (1921–1924)	184,100
Mean 35 years	——	——	205,700	202,600 (34 years)	202,600
Mean 65 years	——	——	211,100	206,700 (64 years)	207,900

*Values not given in report.

†The year 1890 was omitted in the paper by Mr. Shenehon.

ADJUSTMENT FOR STORAGE BETWEEN FIRST AND SECOND GROUPS ABOVE

The computed mean net yield of 214,000 c.f.s. for the 30 years — 1860 to 1889 — is less than the mean measured outflow of 217,450 c.f.s. by 3,450 c.f.s. This is equivalent to 1.305 feet depth on total area of the four lakes.

Also the computed mean net yield of 202,700 c.f.s. for the 35 years — 1890 to 1924 — is less than the mean measured outflow of 205,700 c.f.s. by 3,000 c.f.s. This is equivalent to 1.405 feet depth on total area of the four lakes.

For the combined period of 65 years the computed mean net yield of 207,900 c.f.s. is less than the mean measured outflow by 3,200 c.f.s., which is equivalent to 2.71 feet depth on total area of the four lakes, which checks with the recorded depletion.

ADJUSTMENT FOR CHANGE FROM PAST TO FUTURE CONDITIONS

Since it is now proposed to use these records of the past 65 years, to indicate what may be expected to happen in the future, the changes that have been going on in the past 65 years require compensation before use for computing what would result from regulation under a repetition of precisely the same weather conditions. The noteworthy changes are:

(1) The opening of the Chicago Canal in 1900 with a diversion from Lake Michigan into the Illinois and Mississippi Rivers for that year averaging 2,990 c.f.s., and gradually increasing to an average in 1924, of 9,465 c.f.s., as given year by year, in table on page 172.

(2) The large increase in diversion from Lake Erie at Port Colborne by the Welland Canal, and delivered into Lake Ontario without passing through the gaging station on the Niagara River, most of which is used for power development.

(3) The change in diversion from the old Erie Canal to the Barge Canal, now called the new Erie Canal. This discharge, together with that taken into the Black Rock Canal, which does pass the Niagara gaging stations, is returned into Lake Ontario, like the water diverted by the Welland Canal.

(4) A correction for the lessening of the winter discharge by ice, which is required, since formulas used for computing the discharge from the records of elevation of lakes are deterined under ice-free conditions.

The several diversions for navigation, sanitation and power are described with much detail in the Warren Report of 1922, pages 104 to 233.

DIVERSIONS BY WELLAND CANAL

The diversion by the Welland Canal from Lake Erie at Port Colborne, is mainly for power, which continues throughout the season of no navigation. The Warren Report, page 116, estimates that in 1917 the diversion by Welland Canal during the open season was 4,600 c.f.s., and in the closed season, 4,300 c.f.s., and that in 1918 the diversions were 4,400 c.f.s. and 4,100 c.f.s., respectively, and that in addition to those amounts an average amount of 40 c.f.s. was taken away from Grand River that otherwise would have reached Lake Erie.

The diversion from Grand River for the Welland Canal began in 1833, and that directly into the Welland Canal from Lake Erie, in 1881, or 21 years later than the beginning of these Great Lakes records of elevation and discharge used in the present estimates.

The large increase in amount diverted into the Welland Canal has been made recently for purposes of power development at Meritton, Thorold and St. Catherines, and is described in the Warren Report, page 195 to 198.

The largest power development, of about 50,000 H.P., appears to have been completed about 1908, and the total diversions year by year from Lake Erie appear to have been approximately as follows:

1860 to 1882	40 c.f.s.	1910	3000 c.f.s.
1882 to 1900	1000 c.f.s.	1916	4000 c.f.s.
1908	2000 c.f.s.		

Some years hence, when the New Welland Canal is opened, the requirement of water taken out from Lake Erie for navigation purposes will increase. The present diversion for power through the Welland Canal is less efficiently used than the water diverted from Chippewa at Queenston and it is assumed will not be increased.

DIVERSIONS BY BLACK ROCK AND ERIE CANALS

The diversion by the Black Rock and Erie Canals also have been a variable quantity. The old Erie Canal which took its diversion at Buffalo, above the gaging stations on the Niagara River, is now abandoned between Buffalo and Tonawanda, and parts are being filled.

The "Barge Canal" is now called the "New Erie Canal" and takes its diversion at Tonawanda, below the Gaging Station near the head of Niagara River.

The Black Rock Canal was built to give ship passage around the shallows and rapids at the outlet of Lake Erie into the Niagara River. Its lock, of 5 feet lift, is at Squaw Island, 3½ miles downstream from Lake Erie, just below the "open section" gaging station. The new lock was completed in 1913. It would have its lift lessened materially by the backwater from the dam at Chippawa, proposed in the present report, and would become of little use after the proposed regulation works are put into full operation and particularly after the gorge at the present rapids is widened, as naturally will follow when the project of 25 ft. or 30 ft. waterway from the Great Lakes to the sea is carried out.

The Warren Report, page 120, states that the requirement for lockage and waste at this lock, averaged 50 c.f.s., while leakage from this canal back into the Niagara River along the upper portion of Bird Island, or upstream from the gauging station, was 250 c.f.s. On page 122 of the Warren Report, it is stated that "Altogether, the probable diversion into Black Rock Canal is 700 c.f.s., 300 c.f.s. of which is returned within 3½ miles." This would leave only 400 c.f.s. escaping the gaging station, which is only one-fifth of one per cent of the quantity gaged, and practically inappreciable.

The old Erie Canal was supplied from the Black Rock Canal to the extent sometimes as great as 1,000 c.f.s. But, since 1918, probably its average draft has not exceeded 400 c.f.s., which is spilled into the Niagara River at Tonawanda.

The new Erie Canal receives its supply direct from the Niagara River at Tonawanda, down-stream from the measuring station.

Page 123 of the Warren Report states that the western portion of the barge canal was opened in 1918, and that while no accurate record of the quantity diverted from the Niagara River has been kept, it is believed this is less than the estimated ultimate requirement of 1,237 c.f.s.

During construction from 1910 to 1918, there was at times no diversion. Prior to 1910, the diversion from Lake Erie by way of Black Rock and Erie Canals ranged approximately from 500 c.f.s. to 1,000 c.f.s., about half of which was used for power.

All of these diversions from Lake Erie by this Canal system are returned to Lake Ontario, except what is lost by evaporation and seepage.

The combined Black Rock and Erie Canal diversion has been figured at an average of 1,000 c.f.s. from 1860 to 1918, and since that time to 1924, figured at an average of 500 c.f.s.; with probabilities of a yearly average of 1,000 to 1,500 c.f.s. for the long future.

CORRECTIONS FOR CANAL DIVERSIONS

In the estimates now made for the future water supply these compensations for diversion by Chicago, Welland, Black Rock and Erie Canals have been applied year by year for completeness, notwithstanding that the effect of the changes from the amounts diverted in past years to the amounts likely to be diverted in future has no important effect on results, being all less than uncertainties due to lack of precision of measurement or to improbability of exact repetition in future of the water yield of past years, which is largely dependent on climate.

CORRECTION FOR OBSTRUCTION BY ICE

Most of the discharges published prior to the Warren Report have been too large for winter months because of the ice-free discharge formula having been used without deduction for retardation by ice.

The effect of ice in retarding flow is variable from day to day, and very different in different years. Unfortunately, precise measurements of its effect have been made only on rare occasions. Fortunately, however, at Niagara this ice effect is small, and the values used by Mr. Shenehon in his report of 1919 and 1924 have been used, because of his long personal familiarity with the conditions. These comprise a constant deduction for ice effect in January of 6,000 c.f.s. and in February of 9,000 c.f.s. and no deduction in other months.

The most precise method of correcting the record so as to represent present or future conditions, is to add year by year in the past, the amount of these diversions to the outflow gaged at the measuring station on the Niagara River; and then deduct the amount of the probable future diversions year by year. The computations assume that the Chicago, Welland, and Erie diversions will continue at about their present rate for an indefinite period. If the Chicago diversion is cut in half, some other may increase to offset the reduction.

The errors and uncertainties involved in these adjustments between past and future conditions are small. If all these corrections and adjustments were neglected the error in the final result would be of no significance.

This matter has been discussed on pages 36 and 37, where there is given a summary of the average corrections used in correcting the rates of discharge computed from open-season formulas.

The writer, after study of data, has deemed the adjustments for ice obstruction given in the Warren Report and the Shenehon Report sufficiently accurate for present needs; and after a critical review of the data published in the reports of the U. S. Chief of Engineers, the International Waterways Commission, and in the thousand pages of searching criticism in the Transcript of Record, before the U. S. Supreme Court, has accepted without further question the figures of average monthly rate of discharge for each lake, given recently by the U. S. Lakes Survey Office.

The ice corrections used in the Warren Report and in the Shenehon Report are the same for the same months in every year, being average values, notwithstanding the fact that in many years, Winter weather conditions have been such that there was no important retardation of discharge from Lake Huron or Lake Erie by ice.

Doubtless, it would be possible, by means of slow and patient investigation of many observations at water-works intakes and at many other engineering works along the river banks, and by a patient study of all the charts of the recording pages at lake outlets, and by a painstaking search through old newspaper files, to pick out definitely the periods of possible ice obstruction, and it would then be possible to make a somewhat more accurate compensation for ice effect upon the discharge year by year than is given by these average values for ice obstruction which have been used.

"BUDGETING" THE DISCHARGE OF THE GREAT LAKES

By this term, which is somewhat novel in water power reports, introduced by Mr. F. C. Shenehon in his extremely valuable reports upon regulating the Niagara and St. Lawrence Rivers, is meant the taking account of the available water income, and studying how to conserve, store and expend this water most economically, in maintaining most regular and uniform flow for both power development and navigation, first storing the surplus by raising the lake levels and later carefully restricting the extent of the drawing down by release from storage, lest depths for navigation suffer.

Storing the surplus in years of plenty and carefully measuring it out in years of scarcity, obviously, will permit a larger supply than otherwise to the hydro-electric plants and give a greater depth in seasons of extremely low water than would otherwise be available at the entrance to the St. Lawrence locks and in other navigation channels.

To work this out in detail is a slow and somewhat tedious problem because of the complicated relation between the discharges and levels of the several Great Lakes. It is best done by means of the computation method known to engineers as "Mass-curves", and by first combining the available yields and storage capacities of all the lakes as if all were found in a single lake.

The writer has had this worked out in an approximate way, independently by two different engineer assistants, taking as data the yearly and monthly discharges as given in the records of the U. S. Army Engineers in charge of Lake Surveys, accepting their estimates of proper deductions for the retarding effects of ice cover over the channels between the lakes, which it is widely recognized by all concerned should be made in severe winter weather.

Meanwhile the present data on river discharge and the results of computation on its storage and release and the resulting depth are certainly accurate enough for all present practical purposes.

COMPUTATION OF 65 YEAR MASS CURVE OF YIELD OF NIAGARA RIVER

Computed by A. C. CHICK

Date — Year and Month	Monthly Mean Outflow from Lake Erie thru Niagara River as computed from Elev. of Lake Erie *	Deduct to obtain original computed discharge of Niagara River *	Deduct for obstruction of flow due to ice — January 6000 c.f.s. — February 9000 c.f.s.	Add for estimated diversion thru Welland Canal	Add for estimated diversion thru Erie and Black Rock Canals	Add for estimated diversion thru Chicago Drainage Canal	Add or Subtract for Rise or Fall of weighed average level of 4 lakes — Total area 87,845 Sq. Mi. — Mean for each month used		Total correction to be applied to Column I per sum of columns II, III, IV V, VI, VIII	Total net Water Yield of 4 lakes Superior Michigan Huron and Erie — Columns I and IX	Excess Yield over constant minimum draft of 193,000 c.f.s. including diversions		
							Weighted Rise or Fall of surface of 4 lakes	Equivalent quantity to or from storage			Column X minus 193,000 c.f.s.	Equivalent weighted average depth on 4 lakes Column XI ÷ 933,000	Progressive algebraic summation of monthly w'ghted average depths on 4 lakes
	I 100 c.f.s.	II c.f.s.	III c.f.s.	IV c.f.s.	V c.f.s.	VI c.f.s.	VII Feet	VIII 100 c.f.s.	IX 100 c.f.s.	X 100 c.f.s.	XI 100 c.f.s.	XII Feet	XIII Feet
1860													
Jan.	2321	2100	6000	....	1000	....	...	....	— 71	2250	+ 320	+.034	0.034
Feb.	2178	2100	9000	....	1000	....	—.041	— 382	— 473	1705	— 225	—.024	0.010
Mar.	2265	2100	....	....	1000	....	+.063	+ 588	+ 577	2842	+ 912	+.098	0.108
Apr.	2423	2100	....	....	1000	....	+.333	+3109	+3098	5521	+3591	+.385	0.493
May	2475	2100	....	....	1000	....	+.171	+1595	+1584	4059	+2129	+.228	0.721
June	2486	2100	....	....	1000	....	+.120	+1120	+1109	3595	+1665	+.178	0.899
July	2436	2100	....	....	1000	....	—.025	— 233	— 244	2192	+ 262	+.028	0.927
Aug.	2375	2100	....	....	1000	....	—.099	— 924	— 935	1440	— 490	—.053	0.874
Sept.	2304	2100	....	....	1000	....	—.151	—1409	—1420	884	—1046	—.112	0.762
Oct.	2244	2100	....	....	1000	....	—.181	—1689	—1700	544	—1386	—.148	0.614
Nov.	2248	2100	....	....	1000	....	—.243	—2265	—2275	— 27	—1957	—.210	0.404
Dec.	2256	2100	....	....	1000	....	—.233	—2175	—2186	70	—1860	—.199	0.205
Mean	**2334**	**2100**	1250	....	1000	....	**—.286**†	**— 222**	**— 246**	**2088**	**+ 158**	**+.205**	....
1861													
Jan.	2161	2100	6000	....	1000	....	—.161	—1501	—1572	589	—1341	—.144	0.061
Feb.	2045	2100	9000	....	1000	....	—.078	— 728	— 829	1216	— 714	—.076	0.015
Mar.	2136	2100	....	....	1000	....	+.202	+1885	+1874	4010	+2180	+.233	0.218
Apr.	2375	2100	....	....	1000	....	+.325	+3030	+3019	5394	+3464	+.371	0.589
May	2485	2100	....	....	1000	....	+.498	+4650	+4639	7124	+5194	+.556	1.145
June	2521	2100	....	....	1000	....	+.146	+1362	+1351	3872	+1942	+.208	1.353
July	2474	2100	....	....	1000	....	+.096	+ 895	+ 884	3358	+1428	+.153	1.506
Aug.	2436	2100	....	....	1000	....	+.114	+1065	+1054	3490	+1560	+.167	1.673
Sept.	2431	2100	....	....	1000	....	—.214	—1995	—2006	425	—1505	—.161	1.512
Oct.	2387	2100	....	....	1000	....	—.078	— 728	— 739	1648	— 282	—.030	1.482
Nov.	2410	2100	....	....	1000	....	—.245	—2285	—2296	114	—1816	—.195	1.287
Dec.	2401	2100	....	....	1000	....	—.254	—2370	—2381	20	—1910	—.204	1.083
Mean	**2355**	**2100**	1250	....	1000	....	**+.354**	**+ 275**	**+ 251**	**2606**	**+ 676**	**+.878**	....
1862													
Jan.	2365	2100	6000	....	1000	....	—.232	—2165	—2236	129	—1801	—.193	0.890
Feb.	2237	2100	9000	....	1000	....	—.181	—1689	—1790	447	—1483	—.159	0.731
Mar.	2258	2100	....	....	1000	....	+:182	+1698	+1687	3945	+2015	+.216	0.947
Apr.	2471	2100	....	....	1000	....	+.212	+1978	+1967	4438	+2508	+.268	1.215
May	2531	2100	....	....	1000	....	+.406	+3785	+3774	6305	+4375	+.469	1.684
June	2551	2100	....	....	1000	....	+.063	+ 588	+ 577	3128	+1198	+.128	1.812
July	2562	2100	....	....	1000	....	—.066	— 616	— 627	1935	+ 5	+.001	1.813
Aug.	2439	2100	....	....	1000	....	+.012	+ 112	+ 101	2540	+ 610	+.065	1.878
Sept.	2375	2100	....	....	1000	....	—.029	— 271	— 282	2093	+ 163	+.017	1.895
Oct.	2294	2100	....	....	1000	....	—.127	—1185	—1196	1098	— 832	—.089	1.806
Nov.	2237	2100	....	....	1000	....	—.362	—3375	—3386	—1149	—3079	—.330	1.476
Dec.	2291	2100	....	....	1000	....	—.167	—1558	—1569	722	—1208	—.129	1.347
Mean	**2384**	**2100**	1250	....	1000	....	**—.290**	**— 225**	**— 248**	**2136**	**+ 206**	**+.264**	....
1863													
Jan.	2372	2100	6000	....	1000	....	—.052	— 485	— 556	1816	— 114	—.012	1.335
Feb.	2390	2100	9000	....	1000	....	+.013	+ 121	+ 20	2410	+ 480	+.051	1.386
Mar.	2361	2100	....	....	1000	....	—.074	— 691	— 702	1659	— 271	—.029	1.357
Apr.	2375	2100	....	....	1000	....	+.029	+ 271	+ 260	2635	+ 705	+.075	1.432
May	2418	2100	....	....	1000	....	+.177	+1652	+1641	4059	+2129	+.227	1.659
June	2400	2100	....	....	1000	....	0	0	— 11	2389	+ 459	+.049	1.708
July	2387	2100	....	....	1000	....	+.011	+ 102	+ 91	2478	+ 548	+.059	1.767
Aug.	2346	2100	....	....	1000	....	+.150	+1400	+1389	3735	+1805	+.193	1.960
Sept.	2264	2100	....	....	1000	....	—.131	—1222	—1233	1031	— 899	—.096	1.864
Oct.	2172	2100	....	....	1000	....	—.161	—1502	—1513	659	—1271	—.136	1.728
Nov.	2101	2100	....	....	1000	....	—.401	—3740	—3751	—1650	—3580	—.384	1.344
Dec.	2137	2100	....	....	1000	....	+.130	+1214	+1203	3340	+1410	+.151	1.495
Mean	**2311**	**2100**	1250	....	1000	....	**—.310**	**— 241**	**— 264**	**2047**	**+ 117**	**+.148**	....

*Values in Column I for Niagara River discharge from 1860 to 1907 inclusive were taken from Report of International Waterways Commission on the Regulation of Lake Erie, 1910 as published and include addition for an average constant flow of 1000 c.f.s. through Erie Canal and for average constant flow of 1100 c.f.s. through Welland Canal. This total addition of 2100 c.f.s. forms Column II.

Values for Niagara River Discharge from 1908 to 1924 inclusive were taken from blue print tables furnished by U. S. L. S. office, in December 1924 and March 1925, and do not include addition for discharge through Chicago, Welland and Erie Canals, or deduction for obstruction of flow by ice. These are applied in Columns III, IV, V and VI.

†Heavy figures in this column represent the total weighted average change in elevation of the 4 lakes for the year.

COMPUTATION OF 65 YEAR MASS CURVE (Continued)

	I 100 c.f.s.	II c.f.s.	III c.f.s.	IV c.f.s.	V c.f.s.	VI c.f.s.	VII Feet	VIII 100 c.f.s.	IX 100 c.f.s.	X 100 c.f.s.	XI 100 c.f.s.	XII Feet	XIII Feet
1864													
Jan.	2041	2100	6000	....	1000	....	—.259	—2418	—2489	— 448	—2378	—.255	1.240
Feb.	2025	2100	9000	....	1000	....	—.131	—1223	—1324	701	—1229	—.132	1.108
Mar.	2061	2100	....	....	1000	....	+.180	+1680	+1669	3730	+1800	+.193	1.301
Apr.	2157	2100	....	....	1000	....	—.083	— 775	— 786	1371	— 559	—.060	1.241
May	2332	2100	....	....	1000	....	+.405	+3780	+3769	6101	+4171	+.447	1.688
June	2337	2100	....	....	1000	....	+.044	+ 411	+ 400	2737	+ 807	+.086	1.774
July	2288	2100	....	....	1000	....	—.050	— 467	— 478	1810	— 120	—.013	1.761
Aug.	2203	2100	....	....	1000	....	—.121	—1130	—1141	1062	— 868	—.093	1.668
Sept.	2165	2100	....	....	1000	....	—.111	—1036	—1047	1118	— 812	—.087	1.581
Oct.	2105	2100	....	....	1000	....	—.333	—3110	—3121	—1016	—2946	—.315	1.266
Nov.	2091	2100	....	....	1000	....	—.177	—1651	—1662	429	—1501	—.161	1.105
Dec.	2153	2100	....	....	1000	....	—.113	—1055	—1066	1087	— 843	—.090	1.015
Mean	**2163**	**2100**	**1250**	....	1000	....	—.750	— **583**	— **606**	**1557**	— **373**	—.480	....
1865													
Jan.	2022	2100	6000	....	1000	....	—.225	—2100	—2171	— 149	—2079	—.223	0.792
Feb.	1846	2100	9000	....	1000	....	—.026	— 242	— 343	1503	— 427	—.046	0.746
Mar.	1904	2100	...	....	1000	....	+.078	+ 728	+ 717	2621	+ 691	+.074	0.820
Apr.	2050	2100	....	....	1000	....	+.499	+4660	+4649	6699	+4769	+.511	1.331
May	2183	2100	...	....	1000	....	+.330	+3080	+3069	5252	+3322	+.356	1.687
June	2195	2100	....	....	1000	....	+.168	+1567	+1556	3751	+1821	+.195	1.882
July	2203	2100	....	....	1000	....	+.334	+3115	+3104	5307	+3377	+.362	2.244
Aug.	2165	2100	....	....	1000	....	+.030	+ 280	+ 269	2434	+ 504	+.054	2.298
Sept.	2171	2100	....	....	1000	....	—.063	— 588	— 599	1572	— 358	—.038	2.260
Oct.	2112	2100	....	....	1000	....	—.236	—2200	—2211	— 99	—2029	—.218	2.042
Nov.	2050	2100	....	....	1000	....	—.527	—4920	—4931	—2881	—4811	—.515	1.527
Dec.	2061	2100	....	....	1000	....	—.290	—2705	—2716	— 655	—2585	—.277	1.250
Mean	**2080**	**2100**	**1250**	....	1000	....	+.072	+ **56**	+ **33**	**2113**	+ **183**	+.235	....
1866													
Jan.	1971	2100	6000	....	1000	....	—.272	—2538	—2609	— 638	—2568	—.275	0.975
Feb.	1887	2100	9000	....	1000	....	—.220	—2054	—2155	— 268	—2198	—.235	0.740
Mar.	1962	2100	...	....	1000	....	+.072	+ 672	+ 661	2623	+ 693	+.074	0.814
Apr.	2077	2100	....	....	1000	....	+.466	+4350	+4339	6416	+4486	+.481	1.295
May	2125	2100	....	....	1000	....	+.210	+1960	+1949	4074	+2144	+.230	1.525
June	2206	2100	....	....	1000	....	+.250	+2332	+2321	4527	+2597	+.278	1.803
July	2248	2100	....	....	1000	....	+.253	+2360	+2349	4597	+2667	+.286	2.089
Aug.	2169	2100	....	....	1000	....	+.085	+ 793	+ 782	2951	+1021	+.109	2.198
Sept.	2169	2100	....	....	1000	....	—.183	—1707	—1718	451	—1479	—.158	2.040
Oct.	2181	2100	....	....	1000	....	—.051	— 476	— 487	1694	— 236	—.025	2.015
Nov.	2150	2100	....	....	1000	....	—.195	—1820	—1831	319	—1611	—.173	1.842
Dec.	2197	2100	....	....	1000	....	—.093	— 843	— 854	1343	— 587	—.063	1.779
Mean	**2112**	**2100**	**1250**	....	1000	....	+.323	+ **253**	+ **229**	**2341**	+ **411**	+.529	....
1867													
Jan.	2098	2100	6000	....	1000	....	—.143	—1335	—1406	692	—1238	—.132	1.647
Feb.	1975	2100	9000	....	1000	....	—.052	— 485	— 586	1389	— 541	—.058	1.589
Mar.	2055	2100	....	....	1000	....	+.071	+ 662	+ 651	2706	+ 776	+.083	1.672
Apr.	2112	2100	....	....	1000	....	+.268	+2500	+2489	4601	+2671	+.286	1.958
May	2234	2100	....	....	1000	....	+.174	+1625	+1614	3848	+1918	+.205	2.163
June	2330	2100	....	....	1000	....	+.416	+3880	+3869	6199	+4269	+.457	2.620
July	2298	2100	....	....	1000	....	+.175	+1633	+1622	3920	+1990	+.213	2.833
Aug.	2203	2100	....	....	1000	....	—.117	—1091	—1102	1101	— 829	—.089	2.744
Sept.	2123	2100	....	....	1000	....	—.157	—1465	—1476	647	—1283	—.137	2.607
Oct.	2058	2100	....	....	1000	....	—.218	—2035	—2046	12	—1918	—.205	2.402
Nov.	1970	2100	....	....	1000	....	—.452	—4220	—4231	—2261	—4191	—.449	1.953
Dec.	1964	2100	....	....	1000	....	—.324	—3025	—3036	—1072	—3002	—.321	1.632
Mean	**2118**	**2100**	**1250**	....	1000	....	—.359	— **279**	— **303**	**1815**	— **115**	—.147	....
1868													
Jan.	1891	2100	6000	....	1000	....	—.165	—1540	—1611	280	—1650	—.177	1.455
Feb.	1765	2100	9000	....	1000	....	—.282	—2630	—2731	— 966	—2896	—.310	1.145
Mar.	1878	2100	....	....	1000	....	+.552	+5150	+5139	7017	+5087	+.545	1.690
Apr.	2048	2100	....	....	1000	....	+.117	+1092	+1081	3129	+1199	+.129	1.819
May	2149	2100	....	....	1000	....	+.344	+3210	+3199	5348	+3418	+.366	2.185
June	2261	2100	....	....	1000	....	+.122	+1138	+1127	3388	+1458	+.156	2.341
July	2270	2100	....	....	1000	....	+.092	+ 859	+ 848	3118	+1188	+.127	2.468
Aug.	2125	2100	....	....	1000	....	—.266	—2480	—2491	— 366	—2296	—.246	2.222
Sept.	2077	2100	....	....	1000	....	—.109	—1016	—1027	1050	— 880	—.094	2.128
Oct.	1987	2100	....	....	1000	....	—.181	—1690	—1701	286	—1644	—.176	1.952
Nov.	1976	2100	....	....	1000	....	+.003	+ 28	+ 17	1993	+ 63	+.007	1.959
Dec.	1973	2100	....	....	1000	....	—.326	—3041	—3052	—1079	—3009	—.322	1.637
Mean	**2033**	**2100**	**1250**	....	1000	....	—.100	— **78**	— **101**	**1932**	+ **2**	+.005	....
1869													
Jan.	1941	2100	6000	....	1000	....	—.132	—1232	—1303	638	—1292	—.138	1.499
Feb.	1878	2100	9000	....	1000	....	—.060	— 560	— 661	1217	— 713	—.076	1.423
Mar.	1973	2100	....	....	1000	....	—.241	—2250	—2261	— 288	—2218	—.238	1.185
Apr.	2025	2100	....	....	1000	....	+.438	+4090	+4079	6104	+4174	+.447	1.632
May	2149	2100	....	....	1000	....	+.382	+3565	+3554	5703	+3773	+.404	2.036
June	2261	2100	....	....	1000	....	+.323	+3015	+3004	5265	+3335	+.357	2.393
July	2348	2100	....	....	1000	....	+.364	+3395	+3384	5732	+3802	+.407	2.800
Aug.	2304	2100	....	....	1000	....	+.290	+2705	+2694	4998	+3068	+.328	3.128
Sept.	2251	2100	....	....	1000	....	+.221	+2062	+2051	4302	+2372	+.254	3.382
Oct.	2157	2100	....	....	1000	....	—.429	—4000	—4011	—1854	—3784	—.405	2.977
Nov.	2075	2100	....	....	1000	....	—.240	—2240	—2251	— 176	—2106	—.226	2.751
Dec.	2203	2100	....	....	1000	....	—.340	—3173	—3184	— 981	—2911	—.312	2.439
Mean	**2130**	**2100**	**1250**	....	1000	....	+.576	+ **448**	+ **425**	**2555**	+ **625**	+.807	....

COMPUTATION OF 65 YEAR MASS CURVE (Continued)

	I 100 c.f.s.	II c.f.s.	III c.f.s.	IV c.f.s.	V c.f.s.	VI c.f.s.	VII Feet	VIII 100 c.f.s	IX 100 c.f.s.	X 100 c.f.s	XI 100 c.f.s.	XII Feet	XIII Feet
1870													
Jan.	2229	2100	6000	....	1000	....	—.032	— 299	— 370	1859	— 71	—.008	2.431
Feb.	2231	2100	9000	....	1000	....	—.003	— 28	— 129	2102	+ 172	+.018	2.449
Mar.	2164	2100	....	....	1000	....	+.131	+1222	+1211	3375	+1445	+.155	2.604
Apr.	2306	2100	....	....	1000	....	+.330	+3080	+3069	5375	+3445	+.369	2.973
May	2356	2100	....	....	1000	....	+.320	+2985	+2974	5330	+3400	+.364	3.337
June	2368	2100	....	....	1000	....	0	0	— 11	2357	+ 427	+.047	3.384
July	2395	2100	....	....	1000	....	+.131	+1222	+1211	3606	+1676	+.179	3.563
Aug.	2361	2100	....	....	1000	....	—.052	— 468	— 479	1882	— 48	—.005	3.558
Sept.	2314	2100	....	....	1000	....	+.104	+ 971	+ 960	3274	+1344	+.144	3.702
Oct.	2234	2100	....	....	1000	....	—.310	—2892	—2903	— 669	—2599	—.279	3.423
Nov.	2188	2100	....	....	1000	....	—.308	—2874	—2885	— 697	—2627	—.281	3.142
Dec.	2206	2100	....	....	1000	....	—.534	—4980	—4991	—2785	—4715	—.505	2.637
Mean	**2279**	**2100**	**1250**	....	**1000**	....	**—.222**	**— 172**	**— 196**	**2083**	**+ 153**	**+.198**	....
1871													
Jan.	2123	2100	6000	....	1000	....	+.020	+ 186	+ 115	2238	+ 308	+.033	2.670
Feb.	1997	2100	9000	....	1000	....	—.299	—2790	—2891	— 894	—2824	—.302	2.368
Mar.	2088	2100	....	....	1000	....	+.516	+4815	+4804	6892	+4962	+.532	2.900
Apr.	2185	2100	....	....	1000	....	+.343	+3200	+3189	5374	+3444	+.369	3.269
May	2248	2100	....	....	1000	....	+.406	+3790	+3779	6027	+4097	+.438	3.707
June	2273	2100	....	....	1000	....	+.068	+ 635	+ 624	2897	+ 967	+.103	3.810
July	2285	2100	....	....	1000	....	+.039	+ 364	+ 353	2639	+ 709	+.076	3.886
Aug.	2215	2100	....	....	1000	....	—.122	—1139	—1150	1065	— 865	—.093	3.793
Sept.	2188	2100	....	....	1000	....	—.329	—3070	—3081	— 893	—2823	—.302	3.491
Oct.	2045	2100	....	....	1000	....	—.461	—4305	—4316	—2271	—4201	—.450	3.041
Nov.	2029	2100	....	....	1000	....	—.073	— 681	— 692	1337	— 593	—.063	2.978
Dec.	1973	2100	....	....	1000	....	—.627	—5850	—5861	—3878	—5808	—.622	2.356
Mean	**2137**	**2100**	**1250**	....	**1000**	....	**—.520**	**— 404**	**— 427**	**1710**	**— 220**	**—.281**	....
1872													
Jan.	1925	2100	6000	....	1000	....	—.153	—1428	—1499	426	—1504	—.161	2.195
Feb.	1828	2100	9000	....	1000	....	—.069	— 644	— 745	1083	— 847	—.091	2.104
Mar.	1798	2100	....	....	1000	....	—.168	—1568	—1579	219	—1711	—.183	1.921
Apr.	1825	2100	....	....	1000	....	+.116	+1083	+1072	2897	+ 967	+.104	2.025
May	1917	2100	....	....	1000	....	+.420	+3920	+3909	5826	+3896	+.417	2.442
June	2016	2100	....	....	1000	....	+.374	+3490	+3471	5487	+3557	+.381	2.823
July	2029	2100	....	....	1000	....	+.113	+1054	+1043	3072	+1142	+.122	2.945
Aug.	2005	2100	....	....	1000	....	+.048	+ 448	+ 437	2442	+ 512	+.055	3.000
Sept.	1966	2100	....	....	1000	....	—.005	— 47	— 58	1908	— 22	—.002	2.998
Oct.	1941	2100	....	....	1000	....	—.119	—1110	—1121	820	—1110	—.119	2.879
Nov.	1893	2100	....	....	1000	....	—.244	—2275	—2286	— 393	—2323	—.249	2.630
Dec.	1885	2100	....	....	1000	....	—.478	—4460	—4471	—2586	—4516	—.484	2.146
Mean	**1919**	**2100**	**1250**	....	**1000**	....	**—.165**	**— 128**	**— 152**	**1767**	**— 163**	**—.210**	....
1873													
Jan.	1835	2100	6000	....	1000	....	—.048	— 448	— 519	1316	— 614	—.066	2.080
Feb.	1792	2100	9000	....	1000	....	—.142	—1325	—1426	366	—1564	—.167	1.913
Mar.	1796	2100	....	....	1000	....	+.179	+1670	+1659	3455	+1525	+.163	2.076
Apr.	2061	2100	....	....	1000	....	+.450	+4200	+4189	6250	+4320	+.463	2.539
May	2217	2100	....	....	1000	....	+.588	+5490	+5479	7696	+5766	+.618	3.157
June	2255	2100	....	....	1000	....	+.443	+4135	+4124	6379	+4449	+.476	3.633
July	2267	2100	....	....	1000	....	+.083	+ 774	+ 763	3030	+1100	+.118	3.751
Aug.	2231	2100	....	....	1000	....	+.110	+1026	1015	3246	+1316	+.141	3.892
Sept.	2150	2100	....	....	1000	....	—.124	—1156	—1167	983	— 947	—.101	3.791
Oct.	2094	2100	....	....	1000	....	—.103	— 962	— 973	1121	— 809	—.087	3.704
Nov.	2072	2100	....	....	1000	....	—.193	—1800	—1811	261	—1669	—.179	3.525
Dec.	2206	2100	....	....	1000	....	—.086	— 802	— 813	1393	— 537	—.057	3.468
Mean	**2081**	**2100**	**1250**	....	**1000**	....	**+1.156**	**+ 899**	**+ 876**	**2957**	**+1027**	**+1.322**	....
1874													
Jan.	2269	2100	6000	....	1000	....	—.138	—1289	—1360	909	—1021	—.109	3.359
Feb.	2227	2100	9000	....	1000	....	+.148	+1381	+1280	3507	+1577	+.169	3.528
Mar.	2221	2100	....	....	1000	....	+.066	+ 616	+ 605	2826	+ 896	+.096	3.624
Apr.	2246	2100	....	....	1000	....	+.005	+ 47	+ 36	2282	+ 352	+.038	3.662
May	2267	2100	....	....	1000	....	+.026	+ 243	+ 232	2499	+ 569	+.061	3.723
June	2301	2100	....	....	1000	....	+.272	+2536	+2525	4826	+2896	+.310	4.033
July	2327	2100	....	....	1000	....	+.106	+ 990	+ 979	3306	+1376	+.147	4.180
Aug.	2267	2100	....	....	1000	....	+.019	+ 177	+ 166	2433	+ 503	+.054	4.234
Sept.	2170	2100	....	....	1000	....	—.147	—1390	—1401	769	—1161	—.124	4.110
Oct.	2079	2100	....	....	1000	....	—.211	—1969	—1980	99	—1831	—.196	3.914
Nov.	2009	2100	....	....	1000	....	—.219	—2044	—2055	— 46	—1976	—.212	3.702
Dec.	2005	2100	....	....	1000	....	—.313	—2920	—2931	— 926	—2856	—.306	3.396
Mean	**2199**	**2100**	**1250**	....	**1000**	....	**—.386**	**— 300**	**— 324**	**1875**	**— 55**	**—.072**	....
1875													
Jan.	1923	2100	6000	....	1000	....	—.247	—2305	—2376	— 453	—2383	—.255	3.141
Feb.	1840	2100	9000	....	1000	....	—.071	— 662	— 763	+1080	— 850	—.091	3.050
Mar.	1860	2100	....	....	1000	....	+.062	+ 578	+ 567	2427	+ 497	+.053	3.103
Apr.	1929	2100	....	....	1000	....	+.233	+2173	+2162	4091	+2161	+.231	3.334
May	2033	2100	....	....	1000	....	+.373	+3480	+3469	5502	+3572	+.383	3.717
June	2149	2100	....	....	1000	....	+.358	+3340	+3329	5478	+3548	+.380	4.097
July	2197	2100	....	....	1000	....	—.004	— 37	— 48	2149	+ 219	+.023	4.120
Aug.	2176	2100	....	....	1000	....	+.119	+1110	+1099	3275	+1345	+.145	4.265
Sept.	2157	2100	....	....	1000	....	+.031	+ 289	+ 278	2435	+ 505	+.054	4.319
Oct.	2056	2100	....	....	1000	....	—.191	—1782	—1793	263	—1667	—.178	4.141
Nov.	2047	2100	....	....	1000	....	—.177	—1650	—1661	386	—1544	—.165	3.976
Dec.	2143	2100	....	....	1000	....	—.145	—1352	—1363	780	—1150	—.123	3.853
Mean	**2043**	**2100**	**1250**	....	**1000**	....	**+.342**	**+ 265**	**+ 241**	**2284**	**+ 354**	**+.457**	....

COMPUTATION OF 65 YEAR MASS CURVE (Continued)

	I 100 c.f.s.	II c.f.s.	III c.f.s.	IV c.f.s.	V c.f.s.	VI c.f.s.	VII Feet	VIII 100 c.f.s.	IX 100 c.f.s.	X 100 c.f.s.	XI 100 c.f.s.	XII Feet	XIII Feet
1876													
Jan.	2102	2100	6000	....	1000	....	—.103	— 961	—1032	1070	— 860	—.092	3.761
Feb.	2183	2100	9000	....	1000	....	+.093	+ 868	+ 767	2950	+1020	+.109	3.870
Mar.	2332	2100	....	....	1000	....	+.215	+2005	+1994	4326	+2396	+.257	4.127
Apr.	2446	2100	....	....	1000	....	+.176	+1642	+1631	4077	+2147	+.230	4.357
May	2528	2100	....	....	1000	....	+.555	+5180	+5169	7697	+5767	+.618	4.975
June	2578	2100	....	....	1000	....	+.473	+4415	+4404	6982	+5052	+.541	5.516
July	2567	2100	....	....	1000	....	+.304	+2836	+2825	5392	+3462	+.371	5.887
Aug.	2465	2100	....	....	1000	....	—.032	— 298	— 309	2156	+ 226	+.024	5.911
Sept.	2435	2100	....	....	1000	....	—.086	— 802	— 813	1622	— 308	—.033	5.878
Oct.	2317	2100	....	....	1000	....	—.483	—4510	—4521	—2204	—4134	—.442	5.436
Nov.	2365	2100	....	....	1000	....	+.003	+ 28	+ 17	2372	+ 442	+.047	5.483
Dec.	2327	2100	....	....	1000	....	—.385	—3590	—3601	—1274	—3204	—.343	5.140
Mean	**2387**	**2100**	**1250**	....	**1000**	....	**+.730**	**+ 567**	**+ 543**	**2930**	**+1000**	**+1.287**	....
1877													
Jan.	2196	2100	6000	....	1000	....	—.250	—2334	—2405	—1209	—2139	—.229	4.911
Feb.	2105	2100	9000	....	1000	....	—.102	— 952	—1053	1052	— 878	—.094	4.817
Mar.	2041	2100	....	....	1000	....	—.122	—1138	—1149	892	—1038	—.111	4.706
Apr.	2124	2100	....	....	1000	....	+.218	+2035	+2024	4148	+2218	+.238	4.944
May	2181	2100	....	....	1000	....	—.030	— 280	— 291	1890	— 40	—.004	4.940
June	2217	2100	....	....	1000	....	+.126	+1176	+1165	3382	+1452	+.156	5.096
July	2294	2100	....	....	1000	....	+.152	+1419	+1430	3724	+1794	+.192	5.288
Aug.	2239	2100	....	....	1000	....	—.057	— 532	— 543	1696	— 234	—.025	5.263
Sept.	2234	2100	....	....	1000	....	—.176	—1642	—1653	581	—1349	—.145	5.118
Oct.	2152	2100	....	....	1000	....	—.043	— 401	— 412	1740	— 190	—.020	5.098
Nov.	2159	2100	....	....	1000	....	—.148	—1381	—1392	767	—1163	—.125	4.973
Dec.	2225	2100	....	....	1000	....	—.047	— 439	— 450	1775	— 155	—.016	4.957
Mean	**2181**	**2100**	**1250**	....	**1000**	....	**—.480**	**— 372**	**— 395**	**1786**	**— 144**	**—.183**	....
1878													
Jan.	2213	2100	6000	....	1000	....	—.096	— 895	— 966	1247	— 683	—.073	4.884
Feb.	2195	2100	9000	....	1000	....	+.024	+ 224	+ 123	2318	+ 388	+.042	4.926
Mar.	2213	2100	....	....	1000	....	—.182	—1698	—1709	504	—1426	—.153	4.773
Apr.	2298	2100	....	....	1000	....	+.049	+ 457	+ 446	2744	+ 814	+.087	4.860
May	2356	2100	....	....	1000	....	+.282	+2630	+2619	4975	+3045	+.326	5.186
June	2375	2100	....	....	1000	....	+.174	+1622	+1611	3986	+2056	+.221	5.407
July	2393	2100	....	....	1000	....	+.031	+ 289	+ 278	2671	+ 741	+.079	5.486
Aug.	2317	2100	....	....	1000	....	—.235	—2190	—2201	116	—1814	—.194	5.292
Sept.	2298	2100	....	....	1000	....	—.181	—1688	—1699	599	—1331	—.143	5.149
Oct.	2227	2100	....	....	1000	....	—.073	— 681	— 692	1535	— 395	—.042	5.107
Nov.	2206	2100	....	....	1000	....	—.164	—1530	—1541	665	—1265	—.135	4.972
Dec.	2271	2100	....	....	1000	....	—.272	—2540	—2551	— 280	—2210	—.237	4.735
Mean	**2280**	**2100**	**1250**	....	**1000**	....	**—.643**	**— 500**	**— 523**	**1757**	**— 173**	**—.222**	....
1879													
Jan.	2137	2100	6000	....	1000	....	—.173	—1623	—1694	443	—1487	—.159	4.576
Feb.	2055	2100	9000	....	1000	....	—.026	— 243	— 344	1711	— 219	—.023	4.553
Mar.	2051	2100	....	....	1000	....	+.134	+1250	+1231	3282	+1352	+.145	4.698
Apr.	2118	2100	....	....	1000	....	—.105	— 980	— 991	1127	— 803	—.086	4.612
May	2149	2100	....	....	1000	....	—.047	— 438	— 449	1700	— 230	—.025	4.587
June	2187	2100	....	....	1000	....	+.131	+1222	+1211	3398	+1468	+.157	4.744
July	2213	2100	....	....	1000	....	+.138	+1287	+1276	3489	+1559	+.167	4.911
Aug.	2140	2100	....	....	1000	....	—.080	— 746	— 757	1383	— 547	—.059	4.852
Sept.	2077	2100	....	....	1000	....	—.141	—1315	—1326	751	—1179	—.126	4.726
Oct.	2038	2100	....	....	1000	....	—.108	—1007	—1018	1020	— 910	—.097	4.629
Nov.	1956	2100	....	....	1000	....	—.199	—1855	—1866	90	—1840	—.197	4.432
Dec.	2059	2100	....	....	1000	....	—.063	— 588	— 599	1460	— 470	—.050	4.382
Mean	**2098**	**2100**	**1250**	....	**1000**	....	**—.539**	**— 419**	**— 443**	**1655**	**— 275**	**—.353**	....
1880													
Jan.	2146	2100	6000	....	1000	....	—.036	— 336	— 407	1739	— 191	—.020	4.362
Feb.	2103	2100	9000	....	1000	....	—.056	— 522	— 623	1480	— 450	—.048	4.314
Mar.	2124	2100	....	....	1000	....	+.005	+ 46	+ 35	2159	+ 219	+.023	4.337
Apr.	2145	2100	....	....	1000	....	+.117	+1090	+1079	3224	+1294	+.139	4.476
May	2207	2100	....	....	1000	....	+.459	+4280	+4269	6476	+4546	+.487	4.963
June	2251	2100	....	....	1000	....	+.579	+5400	+5389	7640	+5710	+.612	5.575
July	2291	2100	....	....	1000	....	+.179	+1670	+1659	3950	+2020	+.216	5.791
Aug.	2213	2100	....	....	1000	....	—.016	— 149	— 160	2053	+ 123	+.013	5.804
Sept.	2172	2100	....	....	1000	....	—.182	—1697	—1708	464	—1466	—.157	5.647
Oct.	2081	2100	....	....	1000	....	—.246	—2295	—2306	— 225	—2155	—.231	5.416
Nov.	2088	2100	....	....	1000	....	—.196	—1828	—1839	249	—1681	—.180	5.236
Dec.	2055	2100	....	....	1000	....	—.223	—2080	—2091	— 36	—1966	—.210	5.026
Mean	**2156**	**2100**	**1250**	....	**1000**	....	**+.383**	**+ 298**	**+ 275**	**2431**	**+ 501**	**+.644**	....
1881													
Jan.	1931	2100	6000	....	1000	....	—.139	—1297	—1368	563	—1367	—.146	4.880
Feb.	1908	2100	9000	....	1000	....	+.085	+ 793	+ 692	2600	+ 670	+.072	4.952
Mar.	1968	2100	....	....	1000	....	+.155	+1445	+1434	3402	+1472	+.158	5.110
Apr.	2112	2100	....	....	1000	....	+.004	+ 37	+ 26	2138	+ 208	+.022	5.132
May	2205	2100	....	....	1000	....	+.420	+3920	+3909	6114	+4184	+.448	5.580
June	2281	2100	....	....	1000	....	+.308	+2873	+2862	5143	+3213	+.344	5.924
July	2286	2100	....	....	1000	....	0	0	— 11	2275	+ 345	+.037	5.961
Aug.	2188	2100	....	....	1000	....	—.020	— 186	— 197	1991	+ 61	+.007	5.968
Sept.	2119	2100	....	....	1000	....	—.076	— 709	— 720	1399	— 531	—.057	5.911
Oct.	2121	2100	....	....	1000	....	+.288	+2687	+2676	4797	+2867	+.307	6.218
Nov.	2105	2100	....	....	1000	....	—.134	—1250	—1271	834	—1096	—.117	6.101
Dec.	2200	2100	....	....	1000	....	—.129	—1204	—1215	985	— 955	—.102	5.999
Mean	**2119**	**2100**	**1250**	....	**1000**	....	**+.762**	**+ 592**	**+ 568**	**2687**	**+ 757**	**+.973**	....

COMPUTATION OF 65 YEAR MASS CURVE (Continued)

	I 100 c.f.s.	II c.f.s.	III c.f.s.	IV c.f.s.	V c.f.s.	VI c.f.s.	VII Feet	VIII 100 c.f.s.	IX 100 c.f.s.	X 100 c.f.s.	XI 100 c.f.s.	XII Feet	XIII Feet
1882													
Jan.	2283	2100	6000	1000	1000	....	—.186	—1735	—1796	487	—1443	—.155	5.844
Feb.	2229	2100	9000	1000	1000	....	—.096	— 896	— 987	1242	— 688	—.074	5.770
Mar.	2330	2100	....	1000	1000	....	+.204	+1904	+1903	4233	+2303	+.247	6.017
Apr.	2367	2100	....	1000	1000	....	+.064	+ 598	+ 597	2964	+1034	+.111	6.128
May	2416	2100	....	1000	1000	....	+.134	+1250	+1249	3665	+1735	+.186	6.314
June	2474	2100	....	1000	1000	....	+.165	+1540	+1539	4013	+2083	+.223	6.537
July	2474	2100	....	1000	1000	....	+.223	+2080	+2079	4553	+2623	+.281	6.818
Aug.	2416	2100	....	1000	1000	....	+.125	+1666	+1165	3581	+1651	+ 177	6.995
Sept.	2362	2100	....	1000	1000	....	—.079	— 737	— 738	1624	— 306	—.033	6.962
Oct.	2265	2100	....	1000	1000	....	—.327	—3050	—3051	— 786	—2716	—.291	6.671
Nov.	2213	2100	....	1000	1000	....	—.154	—1436	—1437	776	—1154	—.124	6.547
Dec.	2135	2100	....	1000	1000	....	—.300	—2800	—2811	— 676	—2606	—.279	6.268
Mean	**2330**	**2100**	**1250**	**1000**	**1000**	....	**—.228**	**— 177**	**— 190**	**2140**	**+ 210**	**+.269**	....
1883													
Jan.	2084	2100	6000	1000	1000	....	—.228	—2128	—2189	— 105	—2035	—.218	6.050
Feb.	2081	2100	9000	1000	1000	....	—.060	— 540	— 631	1450	— 480	—.051	5.999
Mar.	2115	2100	....	1000	1000	....	+.068	+ 635	+ 634	2749	+ 819	+.088	6.087
Apr.	2126	2100	....	1000	1000	....	+.214	+1998	+1997	4123	+2193	+.235	6.322
May	2234	2100	....	1000	1000	....	+.306	+2855	+2854	5088	+3158	+.337	6.659
June	2427	2100	....	1000	1000	....	+.305	+2845	+2844	5271	+3341	+.358	7.017
July	2500	2100	....	1000	1000	....	+.425	+3970	+3969	6469	+4539	+.486	7.503
Aug.	2462	2100	....	1000	1000	....	—.015	— 140	— 141	2321	+ 391	+.042	7.545
Sept.	2397	2100	....	1000	1000	....	—.150	—1400	—1401	996	— 934	—.100	7.445
Oct.	2332	2100	....	1000	1000	....	—.225	—2100	—2101	231	—1699	—.182	7.263
Nov.	2265	2100	....	1000	1000	....	—.332	—3100	—3101	— 836	—2766	—.296	6.967
Dec.	2320	2100	....	1000	1000	....	—.078	— 728	— 729	1591	— 339	—.036	6.931
Mean	**2279**	**2100**	**1250**	**1000**	**1000**	....	**+.230**	**+ 178**	**+ 165**	**2444**	**+ 514**	**+.663**	....
1884													
Jan.	2206	2100	6000	1000	1000	....	—.178	—1660	—1721	485	—1445	—.155	6.776
Feb.	2215	2100	9000	1000	1000	....	+.082	+ 765	+ 674	2889	+ 956	+.102	6.878
Mar.	2248	2100	....	1000	1000	....	+.108	+1008	+1007	3255	+1325	+.142	7.020
Apr.	2370	2100	....	1000	1000	....	+.053	+ 495	+ 494	2864	+ 934	+.100	7.120
May	2436	2100	....	1000	1000	....	+.221	+2060	+2059	4495	+2565	+.275	7.395
June	2475	2100	....	1000	1000	....	+.165	+1540	+1539	4014	+2084	+.223	7.618
July	2436	2100	....	1000	1000	....	—.058	— 541	— 542	1894	— 36	—.004	7.614
Aug.	2375	2100	....	1000	1000	....	—.087	— 811	— 812	1563	— 377	—.040	7.574
Sept.	2281	2100	....	1000	1000	....	—.082	— 765	— 766	1515	— 415	—.044	7.530
Oct.	2215	2100	....	1000	1000	....	+.092	+ 859	+ 858	3073	+1143	+.122	7.652
Nov.	2126	2100	....	1000	1000	....	—.279	—2605	—2606	— 480	—2410	—.258	7.394
Dec.	2155	2100	....	1000	1000	....	—.101	— 942	— 943	1212	— 718	—.077	7.317
Mean	**2295**	**2100**	**1250**	**1000**	**1000**	....	**—.065**	**— 50**	**— 64**	**2231**	**+ 301**	**+.386**	....
1885													
Jan.	2081	2100	6000	1000	1000	....	—.100	— 933	— 994	1087	— 843	—.090	7.227
Feb.	1984	2100	9000	1000	1000	....	+.028	+ 261	+ 170	2154	+ 224	+.024	7.251
Mar.	1941	2100	....	1000	1000	....	—.066	— 617	— 618	1323	— 607	—.065	7.186
Apr.	2112	2100	....	1000	1000	....	+.178	+1660	+1659	3771	+1841	+.197	7.383
May	2286	2100	....	1000	1000	....	+.393	+3665	+3664	5950	+4020	+.431	7.814
June	2434	2100	....	1000	1000	....	+.271	+2527	+2526	4960	+3030	+.325	8.139
July	2441	2100	....	1000	1000	....	+.129	+1203	+1202	3643	+1713	+.183	8.322
Aug.	2423	2100	....	1000	1000	....	+.153	+1427	+1426	3849	+1919	+.205	8.527
Sept.	2400	2100	....	1000	1000	....	—.116	—1082	—1083	1317	— 613	—.066	8.461
Oct.	2390	2100	....	1000	1000	....	—.146	—1362	—1363	1027	— 903	—.097	8.364
Nov.	2387	2100	....	1000	1000	....	—.224	—2090	—2091	296	—1634	—.175	8.189
Dec.	2423	2100	....	1000	1000	....	—.276	—2575	—2576	— 153	—2083	—.223	7.966
Mean	**2275**	**2100**	**1250**	**1000**	**1000**	....	**+.224**	**+ 174**	**+ 160**	**2435**	**+ 505**	**+.649**	....
1886													
Jan.	2395	2100	6000	1000	1000	....	+.048	+ 448	+ 387	2782	+ 852	+.091	8.057
Feb.	2195	2100	9000	1000	1000	....	—.124	—1156	—1247	948	— 982	—.105	7.952
Mar.	2103	2100	....	1000	1000	....	+.101	+ 945	+ 944	3047	+1117	+.120	8.072
Apr.	2298	2100	....	1000	1000	....	+.277	+2585	+2584	4882	+2952	+.316	8.388
May	2372	2100	....	1000	1000	....	+.261	+2435	+2434	4806	+2876	+.308	8.696
June	2416	2100	....	1000	1000	....	+.099	+ 924	+ 923	3339	+1409	+.151	8.847
July	2428	2100	....	1000	1000	....	—.075	— 700	— 701	1727	— 203	—.022	8.825
Aug.	2357	2100	....	1000	1000	....	—.176	—1642	—1643	714	—1216	—.130	8.695
Sept.	2307	2100	....	1000	1000	....	—.160	—1492	—1493	814	—1116	—.120	8.575
Oct.	2267	2100	....	1000	1000	....	—.043	— 401	— 402	1865	— 65	—.007	8.568
Nov.	2222	2100	....	1000	1000	....	—.279	—2602	—2603	— 381	—2311	—.248	8.320
Dec.	2246	2100	....	1000	1000	....	—.215	—2005	—2006	240	1690	—.181	8.139
Mean	**2298**	**2100**	**1250**	**1000**	**1000**	....	**—.287**	**— 223**	**— 236**	**2062**	**+ 132**	**+.173**	....
1887													
Jan.	2161	2100	6000	1000	1000	....	—.182	—1697	—1758	403	—1527	—.164	7.975
Feb.	2212	2100	9000	1000	1000	....	+.248	+2311	+2220	4432	+2502	+.268	8.243
Mar.	2383	2100	....	1000	1000	....	+.292	+2722	+2721	5104	+3174	+.340	8.583
Apr.	2372	2100	....	1000	1000	....	+.039	+ 363	+ 362	2734	+ 804	+.086	8.669
May	2427	2100	....	1000	1000	....	+.048	+ 448	+ 447	2874	+ 944	+.101	8.770
June	2465	2100	....	1000	1000	....	+.129	+1202	+1201	3666	+1736	+.186	8.956
July	2423	2100	....	1000	1000	....	+.043	+ 401	+ 400	2823	+ 893	+.096	9.052
Aug.	2322	2100	....	1000	1000	....	—.081	— 755	— 756	1566	— 364	—.039	9.013
Sept.	2244	2100	....	1000	1000	....	—.254	—2369	—2370	— 126	—2056	—.220	8.793
Oct.	2258	2100	....	1000	1000	....	—.328	—3059	—3060	— 802	—2732	—.293	8.500
Nov.	2125	2100	....	1000	1000	....	—.290	—2704	—2705	— 580	—2510	—.269	8.231
Dec.	2170	2100	....	1000	1000	....	—.140	—1305	—1306	864	—1066	—.114	8.117
Mean	**2297**	**2100**	**1250**	**1000**	**1000**	....	**—.476**	**— 370**	**— 384**	**1913**	**— 17**	**—.022**	....

COMPUTATION OF 65 YEAR MASS CURVE (Continued)

	I 100 c.f.s.	II c.f.s.	III c.f.s.	IV c.f.s.	V c.f.s	VI c.f.s.	VII Feet	VIII 100 c.f.s.	IX 100 c.f.s.	X 100 c.f.s.	XI 100 c.f.s.	XII Feet	XIII Feet
1888													
Jan.	2094	2100	6000	1000	1000	....	—.155	—1445	—1506	588	—1342	—.144	7.973
Feb.	1954	2100	9000	1000	1000	....	—.054	— 502	— 593	1361	— 569	—.061	7.912
Mar.	1971	2100	....	1000	1000	....	+.079	+ 738	+ 737	2708	+ 778	+.083	7.995
Apr.	2121	2100	....	1000	1000	....	+.183	+1708	+1707	3828	+1898	+.203	8.198
May	2157	2100	....	1000	1000	....	+.399	+3725	+3724	5881	+3951	+.423	8.621
June	2197	2100	....	1000	1000	....	+.439	+4100	+4099	6296	+4366	+.468	9.089
July	2251	2100	....	1000	1000	....	+.092	+ 858	+ 857	3108	+1178	+.126	9.215
Aug.	2225	2100	....	1000	1000	....	—.022	— 205	— 205	2019	+ 189	+.009	9.224
Sept.	2142	2100	....	1000	1000	....	—.148	—1381	—1382	760	—1170	—.125	9.099
Oct.	2098	2100	....	1000	1000	....	—.206	—1923	—1924	174	—1756	—.188	8.911
Nov.	2064	2100	....	1000	1000	....	—.070	— 653	— 654	1410	— 520	—.056	8.855
Dec.	2133	2100	....	1000	1000	....	—.441	—4120	—4121	—1988	—3918	—.420	8.435
Mean	**2117**	**2100**	**1250**	**1000**	**1000**	....	**+.095**	**+ 74**	**+ 61**	**2178**	**+ 248**	**+.318**	....
1889													
Jan.	2091	2100	6000	1000	1000	....	—.125	—1166	—1227	864	—1066	—.114	8.321
Feb.	2041	2100	9000	1000	1000	....	—.115	—1073	—1164	877	—1053	—.113	8.208
Mar.	1952	2100	....	1000	1000	....	—.091	— 849	— 850	1102	— 828	—.089	8.119
Apr.	2038	2100	....	1000	1000	....	+.052	+ 485	+ 484	2522	+ 592	+.063	8 182
May	2075	2100	....	1000	1000	....	+.190	+1773	+1772	3847	+1917	+.205	8.387
June	2186	2100	....	1000	1000	....	+.331	+3089	+3088	5274	+3344	+.358	8.745
July	2196	2100	....	1000	1000	....	+.186	+1735	+1734	3920	+1990	+.213	8.958
Aug.	2174	2100	....	1000	1000	....	—.091	— 849	— 850	1324	— 606	—.065	8.893
Sept.	2084	2100	....	1000	1000	....	—.086	— 802	— 803	1281	— 649	—.069	8.824
Oct.	1970	2100	....	1000	1000	....	—.238	—2220	—2221	— 251	—2181	—.234	8.590
Nov.	1970	2100	....	1000	1000	....	—.326	—3040	—3041	—1071	—3001	—.322	8.268
Dec.	2041	2100	....	1000	1000	....	—.172	—1605	—1606	435	—1495	—.160	8.108
Mean	**2068**	**2100**	**1250**	**1000**	**1000**	....	**—.484**	**— 376**	**— 390**	**1678**	**— 252**	**—.327**	....
1890													
Jan.	2178	2100	6000	1000	1000	....	+.033	+ 308	+ 247	2425	+ 495	+.053	8.161
Feb.	2133	2100	9000	1000	1000	....	—.033	— 308	— 399	1734	— 196	—.021	8.140
Mar.	2191	2100	....	1000	1000	....	—.084	— 784	— 785	1406	— 524	—.056	8.084
Apr.	2251	2100	....	1000	1000	....	+.212	+1978	+1977	4228	+2298	+.246	8.330
May	2342	2100	....	1000	1000	....	+.236	+2201	+2200	4542	+2612	+.280	8.610
June	2426	2100	....	1000	1000	....	+.420	+3920	+3919	6345	+4415	+.472	9.082
July	2354	2100	....	1000	1000	....	+.100	+ 933	+ 932	3286	+1356	+.145	9.227
Aug.	2237	2100	....	1000	1000	....	—.039	— 364	— 365	1872	— 58	—.006	9.221
Sept.	2152	2100	....	1000	1000	....	—.078	— 728	— 729	1423	— 507	—.054	9.167
Oct.	2150	2100	....	1000	1000	....	—.090	— 840	— 841	1309	— 621	—.066	9.101
Nov.	2196	2100	....	1000	1000	....	—.256	—2388	—2389	— 193	—2123	—.227	8.874
Dec.	2133	2100	....	1000	1000	....	—.340	—3172	—3173	—1040	—2970	—.317	8.557
Mean	**2229**	**2100**	**1250**	**1000**	**1000**	....	**+.081**	**+ 63**	**+ 49**	**2278**	**+ 348**	**+.449**	....
1891													
Jan.	2072	2100	6000	1000	1000	....	—.168	—1566	—1627	445	—1485	—.159	8.398
Feb.	2046	2100	9000	1000	1000	....	—.173	—1614	—1705	341	—1589	—.170	8.228
Mar.	2077	2100	....	1000	1000	....	+.138	+1285	+1285	3362	+1432	+.153	8.381
Apr.	2106	2100	....	1000	1000	....	+.130	+1212	+1211	3317	+1387	+.148	8.529
May	2054	2100	....	1000	1000	....	+.103	+ 961	+ 960	3014	+1084	+.116	8.645
June	2050	2100	....	1000	1000	....	+.112	+1045	+1044	3094	+1164	+.125	8.770
July	2091	2100	....	1000	1000	....	—.026	— 242	— 243	1848	— 82	—.008	8.762
Aug.	2025	2100	....	1000	1000	....	—.043	— 401	— 402	1623	— 307	—.033	8.729
Sept.	1986	2100	....	1000	1000	....	—.162	—1510	—1511	475	—1455	—.156	8.573
Oct.	1903	2100	....	1000	1000	....	—.213	—1987	—1988	— 88	—2018	—.216	8.357
Nov.	1891	2100	....	1000	1000	....	—.298	—2780	—2781	— 890	—2820	—.302	8.055
Dec.	1897	2100	....	1000	1000	....	—.172	—1604	—1605	292	—1638	—.175	7.080
Mean	**2016**	**2100**	**1250**	**1000**	**1000**	....	**—.772**	**— 599**	**— 612**	**1403**	**— 527**	**—.677**	....
1892													
Jan.	1878	2100	6000	1000	1000	....	+.065	+ 605	+ 545	2423	+ 493	+.053	7.933
Feb.	1733	2100	9000	1000	1000	....	—.029	— 271	— 362	1371	— 559	—.060	7.873
Mar.	1775	2100	....	1000	1000	....	—.094	— 876	— 877	898	—1032	—.111	7.762
Apr.	1954	2100	....	1000	1000	....	+.101	+ 943	+ 942	2896	+ 966	+.103	7.865
May	2054	2100	....	1000	1000	....	+.432	+4030	+4029	6083	+4153	+.445	8.310
June	2246	2100	....	1000	1000	....	+.461	+4300	+4299	6545	+4615	+.494	8.804
July	2299	2100	....	1000	1000	....	+.030	+ 280	+ 279	2578	+ 648	+.069	8.873
Aug.	2208	2100	....	1000	1000	....	+.043	+ 401	+ 400	2608	+ 678	+.073	8.946
Sept.	2143	2100	....	1000	1000	....	—.123	—1147	—1148	995	— 935	—.100	8.846
Oct.	2066	2100	....	1000	1000	....	—.226	—2110	—2111	— 45	—1975	—.212	8.634
Nov.	1978	2100	....	1000	1000	....	—.240	—2240	—2241	— 263	—2193	—.235	8.399
Dec.	1973	2100	....	1000	1000	....	—.273	—2547	—2548	— 575	—2505	—.269	8.130
Mean	**2026**	**2100**	**1250**	**1000**	**1000**	....	**+.147**	**+ 114**	**+ 101**	**2127**	**+ 197**	**+.250**	....
1893													
Jan.	1806	2100	6000	1000	1000	....	—.153	—1428	—1489	317	—1613	—.173	7.957
Feb.	1796	2100	9000	1000	1000	....	+.049	+ 457	+ 366	2162	+ 232	+.025	7.982
Mar.	1861	2100	....	1000	1000	....	+.101	+ 943	+ 942	2803	+ 873	+.094	8.076
Apr.	2006	2100	....	1000	1000	....	+.361	+3370	+3369	5375	+3445	+.369	8.445
May	2174	2100	....	1000	1000	....	+.438	+4090	+4089	6263	+4333	+.464	8.909
June	2258	2100	....	1000	1000	....	+.383	+3575	+3574	5832	+3902	+.418	9.327
July	2224	2100	....	1000	1000	....	+.086	+ 812	+ 811	3035	+1105	+.118	9.445
Aug.	2086	2100	....	1000	1000	....	—.105	— 980	— 979	1107	— 823	—.088	9.357
Sept.	2028	2100	....	1000	1000	....	—.243	—2270	—2271	— 243	—2173	—.233	9.124
Oct.	2006	2100	....	1000	1000	....	—.125	—1166	—1167	839	—1101	—.118	9.006
Nov.	2001	2100	....	1000	1000	....	—.307	—2865	—2866	— 865	—2795	—.299	8.707
Dec.	1993	2100	....	1000	1000	....	—.110	—1027	—1028	965	— 965	—.103	8.604
Mean	**2020**	**2100**	**1250**	**1000**	**1000**	....	**+.373**	**+ 290**	**+ 278**	**2293**	**+ 368**	**+.474**	....

COMPUTATION OF 65 YEAR MASS CURVE (Continued)

	I 100 c.f.s.	II c.f.s.	III c.f.s.	IV c.f.s.	V c.f.s.	VI c.f.s.	VII Feet	VIII 100 c.f.s.	IX 100 c.f.s.	X 100 c.f.s.	XI 100 c.f.s.	XII Feet	XIII Feet
1894													
Jan.	1993	2100	6000	1000	1000	....	—.028	— 261	— 322	1671	— 259	—.028	8.576
Feb.	1908	2100	9000	1000	1000	....	—.065	— 607	— 698	1210	— 720	—.077	8.499
Mar.	1931	2100	....	1000	1000	....	+.171	+1596	+1595	3526	+1596	+.171	8.670
Apr.	1974	2100	....	1000	1000	....	+.180	+1680	+1679	3653	+1723	+.185	8.855
May	2088	2100	....	1000	1000	....	+.610	+5695	+5694	7782	+5852	+.627	9.482
June	2181	2100	....	1000	1000	....	+.200	+1866	+1865	4046	+2116	+.227	9.709
July	2150	2100	....	1000	1000	....	+.023	+ 215	+ 214	2364	+ 434	+.046	9.755
Aug.	2040	2100	....	1000	1000	....	—.038	— 355	— 356	1684	— 246	—.026	9.729
Sept.	2002	2100	....	1000	1000	....	—.271	—2530	—2531	— 529	—2459	—.263	9.466
Oct.	2002	2100	....	1000	1000	....	—.139	—1297	—1298	704	—1226	—.131	9.335
Nov	1962	2100	....	1000	1000	....	—.186	—1735	—1736	226	—1704	—.182	9.153
Dec.	1923	2100	....	1000	1000	....	—.258	—2409	—2410	— 487	—2417	—.259	8.894
Mean	**2013**	**2100**	**1250**	**1000**	**1000**	....	**+.199**	**+ 155**	**+ 141**	**2154**	**+ 224**	**+.290**	....
1895													
Jan.	1896	2100	6000	1000	1000	....	—.242	—2258	—2319	— 423	—2353	—.252	8.642
Feb.	1749	2100	9000	1000	1000	....	—.166	—1549	—1640	109	—1821	—.195	8.447
Mar.	1733	2100	....	1000	1000	....	—.076	— 709	— 710	1023	— 907	—.097	8.350
Apr.	1777	2100	....	1000	1000	....	+.097	+ 905	+ 904	2681	+ 751	+.081	8.431
May	1850	2100	....	1000	1000	....	+.244	+2276	+2275	4125	+2195	+.235	8.666
June	1872	2100	....	1000	1000	....	+.153	+1428	+1427	3299	+1369	+.147	8.813
July	1867	2100	....	1000	1000	....	+.003	+ 28	+ 27	1894	— 36	—.004	8.809
Aug.	1838	2100	....	1000	1000	....	—.053	— 495	— 496	1342	— 588	—.063	8.746
Sept.	1842	2100	....	1000	1000	....	—.100	— 933	— 934	908	—1022	—.109	8.637
Oct.	1792	2100	....	1000	1000	....	—.230	—2145	—2146	— 354	—2284	—.245	8.392
Nov.	1691	2100	....	1000	1000	....	—.231	—2155	—2156	— 465	—2395	—.256	8.136
Dec.	1744	2100	....	1000	1000	....	—.152	—1418	—1419	325	—1605	—.172	7.958
Mean	**1804**	**2100**	**1250**	**1000**	**1000**	....	**—.759**	**— 530**	**— 604**	**1230**	**— 730**	**—.936**	....
1896													
Jan.	1775	2100	6000	1000	1000	....	—.020	— 186	— 247	1528	— 402	—.043	7.915
Feb.	1760	2100	9000	1000	1000	....	—.062	— 578	— 669	1091	— 839	—.090	7.825
Mar.	1687	2100	....	1000	1000	....	—.074	— 691	— 692	995	— 935	—.100	7.725
Apr.	1796	2100	....	1000	1000	....	+.179	+1670	+1669	3465	+1535	+.164	7.889
May	1891	2100	....	1000	1000	....	+.426	+3975	+3974	5865	+3935	+.421	8.310
June	1893	2100	....	1000	1000	....	+.336	+3135	+3134	5027	+3097	+.332	8.642
July	1932	2100	....	1000	1000	....	—.023	— 214	— 215	1717	— 213	—.023	8.619
Aug.	1983	2100	....	1000	1000	....	—.004	— 37	— 38	1945	+ 15	+.002	8.621
Sept.	1891	2100	....	1000	1000	....	—.152	—1418	—1419	472	—1458	—.155	8.466
Oct.	1836	2100	....	1000	1000	....	—.171	—1595	—1596	240	—1690	—.181	8.285
Nov.	1842	2100	....	1000	1000	....	—.132	—1231	—1232	610	—1320	—.141	8.144
Dec.	1797	2100	....	1000	1000	....	—.077	— 718	— 719	1078	— 852	—.091	8.053
Mean	**1840**	**2100**	**1250**	**1000**	**1000**	....	**+.227**	**+ 176**	**+ 163**	**2003**	**+ 73**	**+.095**	....
1897													
Jan.	1875	2100	6000	1000	1000	....	—.067	— 625	— 686	1189	— 741	—.079	7.974
Feb.	1781	2100	9000	1000	1000	....	—.019	— 177	— 268	1513	— 417	—.045	7.929
Mar.	1888	2100	....	1000	1000	....	+.175	+1633	+1632	3520	+1590	+.170	8.099
Apr.	2004	2100	....	1000	1000	....	+.164	+1530	+1529	3533	+1663	+.178	8.271
May	2101	2100	....	1000	1000	....	+.416	+3880	+3879	5980	+4050	+.434	8.705
June	2097	2100	....	1000	1000	....	+.271	+2530	+2529	4626	+2696	+.289	8.994
July	2093	2100	....	1000	1000	....	+.206	+1922	+1921	4014	+2084	+.223	9.217
Aug.	2066	2100	....	1000	1000	....	—.006	— 56	— 57	2009	+ 79	+.008	9.225
Sept.	1984	2100	....	1000	1000	....	—.184	—1716	—1717	267	—1623	—.174	9.047
Oct.	1886	2100	....	1000	1000	....	—.281	—2620	—2621	— 735	—2665	—.285	8.762
Nov.	1895	2100	....	1000	1000	....	—.259	—2415	—2416	— 521	—2451	—.263	8.499
Dec.	1921	2100	....	1000	1000	....	—.274	—2555	—2556	— 635	—2565	—.275	8.224
Mean	**1966**	**2100**	**1250**	**1000**	**1000**	....	**+.143**	**+ 111**	**+ 97**	**2063**	**+ 133**	**+.171**	....
1898													
Jan.	1893	2100	6000	2000	1000	....	—.153	—1427	—1478	415	—1515	—.162	8.062
Feb.	1870	2100	9000	2000	1000	....	+.030	+ 280	+ 199	2069	+ 139	+.015	8.077
Mar.	1951	2100	....	2000	1000	....	+.127	+1185	+1194	3145	+1215	+.130	8.207
Apr.	2088	2100	....	2000	1000	....	+.234	+2183	+2192	4280	+2350	+.252	8.459
May	2119	2100	....	2000	1000	....	+.250	+2332	+2341	4460	+2530	+.271	8.730
June	2128	2100	....	2000	1000	....	+.246	+2294	+2303	4431	+2501	+.268	8.998
July	2077	2100	....	2000	1000	....	+.113	+1054	+1063	3140	+1210	+.130	9.128
Aug.	2068	2100	....	2000	1000	....	—.080	— 746	— 737	1331	— 599	—.064	9.064
Sept.	1981	2100	....	2000	1000	....	—.189	—1764	—1755	226	—1704	—.182	8.882
Oct.	1943	2100	....	2000	1000	....	—.051	— 476	— 467	1476	— 454	—.049	8.833
Nov.	1965	2100	....	2000	1000	....	—.299	—2790	—2781	— 816	—2746	—.294	8.539
Dec.	1978	2100	....	2000	1000	....	—.279	—2602	—2593	— 615	—2545	—.272	8.267
Mean	**2005**	**2100**	**1250**	**2000**	**1000**	....	**—.051**	**— 40**	**— 43**	**1962**	**+ 32**	**+.043**	....
1899													
Jan.	1974	2100	6000	2100	1000	....	—.143	—1334	—1384	590	—1340	—.144	8.123
Feb.	1875	2100	9000	2100	1000	....	—.057	— 532	— 612	1263	— 667	—.071	8.052
Mar.	1929	2100	....	2100	1000	....	+.158	+1475	+1485	3414	+1484	+.159	8.211
Apr.	1973	2100	....	2100	1000	....	+.164	+1530	+1540	3513	+1583	+.170	8.381
May	2036	2100	....	2100	1000,	....	+.523	+4880	+4890	6926	+4996	+.535	8.916
June	2079	2100	....	2100	1000	....	+.353	+3295	+3305	5384	+3454	+.370	9.286
July	2066	2100	....	2100	1000	....	+.181	+1689	+1699	3765	+1835	+.197	9.483
Aug.	1983	2100	....	2100	1000	....	—.013	— 121	— 111	1872	— 58	—.006	9.477
Sept.	1941	2100	....	2100	1000	....	—.057	— 532	— 522	1419	— 511	—.055	9.422
Oct.	1850	2100	....	2100	1000	....	—.268	—2500	—2490	— 640	—2570	—.275	9.147
Nov.	1866	2100	....	2100	1000	....	—.132	—1232	—1221	645	—1285	—.138	9.009
Dec.	1954	2100	....	2100	1000	....	—.368	—3435	—3425	—1471	—3401	—.364	8.645
Mean	**1961**	**2100**	**1250**	**2100**	**1000**	....	**+.342**	**+ 266**	**+ 262**	**2223**	**+ 293**	**+.378**	....

COMPUTATION OF 65 YEAR MASS CURVE (Continued)

	I 100 c.f.s.	II c.f.s.	III c.f.s.	IV c.f s	V c.f.s.	VI c.f.s.	VII Feet	VIII 100 c.f.s.	IX 100 c.f.s.	X 100 c.f.s.	XI 100 c.f.s.	XII Feet	XIII Feet
1900													
Jan.	1891	2100	6000	2200	1000	2990	—.210	—1960	—1981	— 90	—2020	—.216	8.429
Feb.	1878	2100	9000	2200	1000	2990	+.016	+ 149	+ 100	1978	+ 48	+.005	8.434
Mar.	1923	2100	....	2200	1000	2990	+.049	+ 457	+ 498	2421	+ 491	+.053	8.487
Apr.	1999	2100	....	2200	1000	2990	+.068	+ 635	+ 676	2675	+ 745	+.080	8.567
May	2038	2100	....	2200	1000	2990	+.205	+1913	+1954	3982	+2052	+.220	8.787
June	2056	2100	....	2200	1000	2990	+.088	+ 829	+ 870	2926	+ 996	+.107	8.894
July	2061	2100	....	2200	1000	2990	+.122	+1139	+1150	3211	+1281	+.137	9.031
Aug.	2034	2100	....	2200	1000	2990	+.215	+2005	+2046	4080	+2150	+.230	9.261
Sept.	1978	2100	....	2200	1000	2990	+.126	+1176	+1217	3195	+1265	+.135	9.396
Oct.	1893	2100	....	2200	1000	2990	+.006	+ 56	+ 97	1990	+ 60	+.006	9.402
Nov.	1927	2100	....	2200	1000	2990	—.092	— 859	— 818	1109	— 821	—.088	9.294
Dec.	1912	2100	....	2200	1000	2990	—.114	—1064	—1002	— 925	—1005	—.108	8.984
Mean	**1966**	**2100**	**1250**	**2200**	**1000**	**2990**	**+.257**	**+ 2[illegible]0**	**+ 227**	**2193**	**+ 263**	**+.339**	....
1901													
Jan.	1876	2100	6000	2300	1000	4046	—.263	—2453	—2461	— 585	—2515	—.269	8.715
Feb.	1755	2100	9000	2300	1000	4046	—.167	—1558	—1596	159	—1771	—.190	8.525
Mar.	1712	2100	....	2300	1000	4046	+.129	+1204	+1256	2968	+1038	+.111	8.636
Apr.	1760	2100	....	2300	1000	4046	+.104	+ 791	+1023	2783	+ 853	+.091	8.727
May	1786	2100	....	2300	1000	4046	+.330	+3080	+3132	4918	+2988	+.320	9.047
June	1896	2100	....	2300	1000	4046	+.111	+1035	+1087	2983	+1053	+.113	9.160
July	1936	2100	....	2300	1000	4046	+.244	+2276	+2328	4264	+2334	+.250	9.410
Aug.	1897	2100	....	2300	1000	4046	+.058	+ 541	+ 593	2490	+ 560	+.060	9.470
Sept.	1908	2100	....	2300	1000	4046	—.172	—1605	—1553	355	—1575	—.169	9.301
Oct.	1861	2100	....	2300	1000	4046	—.220	—2054	—2002	— 141	—2071	—.222	9.079
Nov.	1831	2100	....	2300	1000	4046	—.216	—2015	—1963	— 132	—2062	—.221	8.858
Dec.	1827	2100	....	2300	1000	4046	—.257	—2398	—2346	— 519	—2449	—.262	8.596
Mean	**1837**	**2100**	**1250**	**2300**	**1000**	**4046**	**—.319**	**— 248**	**— 208**	**1629**	**— 301**	**—.388**	....
1902													
Jan.	1836	2100	6000	2400	1000	4302	—.243	—2265	—2248	— 412	—2342	—.250	8.346
Feb.	1706	2100	9000	2400	1000	4302	—.208	—1940	—1953	— 247	—2177	—.233	8.113
Mar.	1739	2100	....	2400	1000	4302	+.104	+ 971	+1027	2766	+ 836	+.089	8.202
Apr.	1855	2100	....	2400	1000	4302	+.120	+1120	+1176	3031	+1101	+.118	8.320
May	1906	2100	....	2400	1000	4302	+.362	+3375	+3431	5337	+3407	+.365	8.685
June	1975	2100	....	2400	1000	4302	+.244	+2275	+2331	4306	+2376	+.254	8.939
July	2130	2100	....	2400	1000	4302	+.332	+3100	+3156	5286	+3356	+.359	9.298
Aug.	2110	2100	....	2400	1000	4302	+.012	+ 112	+ 168	2278	+ 348	+.037	9.335
Sept.	2031	2100	....	2400	1000	4302	—.216	—2015	—1959	72	—1858	—.199	9.136
Oct.	2053	2100	....	2400	1000	4302	—.132	—1232	—1176	877	—1053	—.113	9.023
Nov.	1995	2100	....	2400	1000	4302	—.089	— 830	— 774	1221	— 709	—.076	8.947
Dec.	2009	2100	....	2400	1000	4302	—.257	—2399	—2343	— 334	—2264	—.242	8.705
Mean	**1945**	**2100**	**1250**	**2400**	**1000**	**4302**	**+.029**	**+ 22**	**+ 70**	**2015**	**85**	**+.109**	....
1903													
Jan.	1961	2100	6000	2500	1000	4971	—.244	—2275	—2271	— 310	—2240	—.240	8.465
Feb.	1897	2100	9000	2500	1000	4971	—.004	— 37	— 63	1834	— 96	—.010	8.455
Mar.	1992	2100	....	2500	1000	4971	+.131	+1222	+1286	3278	+1348	+.144	8.599
Apr.	2154	2100	....	2500	1000	4971	+.300	+2799	+2863	5017	+3087	+.331	8.930
May	2159	2100	....	2500	1000	4971	+.230	+2145	+2209	4368	+2438	+.261	9.191
June	2184	2100	....	2500	1000	4971	+.227	+2119	+2183	4367	+2437	+.261	9.452
July	2194	2100	....	2500	1000	4971	+.157	+1465	+1529	3723	+1793	+.192	9.644
Aug.	2110	2100	....	2500	1000	4971	—.037	— 345	— 281	1829	— 101	—.008	9.636
Sept.	2088	2100	....	2500	1000	4971	+.028	+ 261	+ 325	2413	+ 483	+.052	9.688
Oct.	2045	2100	....	2500	1000	4971	—.081	— 756	— 692	1353	— 577	—.062	9.626
Nov.	1966	2100	....	2500	1000	4971	—.323	—3015	—2951	— 985	—2915	—.312	9.314
Dec.	1968	2100	....	2500	1000	4971	—.344	—3210	—3146	—1178	—3108	—.333	8.981
Mean	**2060**	**2100**	**1250**	**2500**	**1000**	**4971**	**+.040**	**+ 31**	**+ 82**	**2142**	**+ 212**	**+.276**	....
1904													
Jan.	1762	2100	6000	2600	1000	4793	—.097	— 905	— 902	860	—1070	—.115	8.866
Feb.	1813	2100	9000	2600	1000	4793	—.052	— 485	— 512	1301	— 629	—.067	8.799
Mar.	1931	2100	....	2600	1000	4793	+.175	+1633	+1696	3627	+1697	+.182	8.981
Apr.	2170	2100	....	2600	1000	4793	+.349	+3256	+3319	5489	+3559	+.381	9.362
May	2252	2100	....	2600	1000	4793	+.324	+3023	+3086	5338	+3408	+.365	9.727
June	2317	2100	....	2600	1000	4793	+.328	+3060	+3123	5440	+3510	+.376	10.103
July	2296	2100	....	2600	1000	4793	+.025	+ 233	+ 296	2592	+ 662	+.071	10.174
Aug.	2225	2100	....	2600	1000	4793	—.056	— 522	— 474	1751	— 179	—.019	10.155
Sept.	2157	2100	....	2600	1000	4793	—.019	— 177	— 114	2043	+ 113	+.012	10.167
Oct.	2103	2100	....	2600	1000	4793	—.043	— 401	— 338	1765	— 165	—.018	10.149
Nov.	2033	2100	....	2600	1000	4793	— 243	—2267	—2204	— 171	—2101	—.225	9.924
Dec.	1993	2100	....	2600	1000	4793	—.363	—3386	—3323	—1330	—3260	—.349	9.575
Mean	**2088**	**2100**	**1250**	**2600**	**1000**	**4793**	**+.328**	**+ 255**	**+ 3[illegible]4**	**2392**	**462**	**+.594**	....
1905													
Jan.	1906	2100	6000	2700	1000	4480	—.206	—1922	—1921	— 15	—1945	—.208	9.367
Feb.	1797	2100	9000	2700	1000	4480	—.190	—1773	—1802	— 5	—1935	—.207	9.160
Mar.	1816	2100	....	2700	1000	4480	+.024	+ 224	+ 285	+2101	+ 171	+.018	9.178
Apr.	1917	2100	....	2700	1000	4480	+.350	+3265	+3326	5243	+3313	+.355	9.533
May	2049	2100	....	2700	1000	4480	+.297	+2770	+2831	4880	+2950	+.316	9.849
June	2188	2100	....	2700	1000	4480	+.329	+3070	+3131	5319	+3389	+.363	10.212
July	2264	2100	....	2700	1000	4480	+.191	+1782	+1843	4107	+2177	+.233	10.445
Aug.	2209	2100	....	2700	1000	4480	+.009	+ 84	+ 145	2354	+ 424	+.045	10.490
Sept.	2161	2100	....	2700	1000	4480	0	0	+ 61	2222	+ 292	+.031	10.521
Oct.	2112	2100	....	2700	1000	4480	—.261	—2435	—2374	— 262	—2192	—.235	10.286
Nov.	2029	2100	....	2700	1000	4480	—.243	—2265	—2204	— 175	—2105	—.225	10.061
Dec.	2066	2100	....	2700	1000	4480	—.156	—1455	—1394	672	—1258	—.135	9.926
Mean	**2043**	**2100**	**1250**	**2700**	**1000**	**4480**	**+.144**	**+ 111**	**+ 160**	**2203**	**+ 273**	**+.351**	....

COMPUTATION OF 65 YEAR MASS CURVE (Continued)

	I 100 c.f.s.	II c.f.s.	III c.f.s.	IV c.f.s.	V c.f.s.	VI c.f.s.	VII Feet	VIII 100 c.f.s.	IX 100 c.f.s.	X 100 c.f.s.	XI 100 c.f.s.	XII Feet	XIII Feet
1906													
Jan.	2038	2100	6000	2800	1000	4473	—.094	— 877	— 875	1163	— 767	—.082	9.844
Feb.	1936	2100	9000	2800	1000	4473	—.030	— 280	— 308	1628	— 302	—.032	9.812
Mar.	1889	2100	....	2800	1000	4473	—.027	— 252	— 190	1699	— 231	—.025	9.787
Apr.	1977	2100	....	2800	1000	4473	+.118	+1101	+1163	3140	+1210	+.130	9.917
May	2025	2100	....	2800	1000	4473	+.287	+2680	+2742	4767	+2837	+.304	10.221
June	2075	2100	....	2800	1000	4473	+.196	+1829	+1891	3966	+2036	+.218	10.439
July	2091	2100	....	2800	1000	4473	+.054	+ 504	+ 566	2657	+ 727	+.078	10.517
Aug.	2078	2100	....	2800	1000	4473	—.006	— 56	+ 6	2084	+ 154	+.016	10.533
Sept.	2025	2100	....	2800	1000	4473	—.207	—1931	—1869	156	—1774	—.190	10.343
Oct.	2020	2100	....	2800	1000	4473	—.155	—1446	—1384	636	—1294	—.139	10.204
Nov.	2036	2100	....	2800	1000	4473	—.153	—1428	—1366	669	—1261	—.135	10.059
Dec.	2066	2100	....	2800	1000	4473	—.073	— 681	— 619	1447	— 483	—.052	10.017
Mean	**2021**	**2100**	**1250**	**2800**	**1000**	**4473**	**—.090**	**— 69**	**— 20**	**2001**	**+ 71**	**+.091**	....
1907													
Jan.	2185	2100	6000	2900	1000	5116	—.074	— 691	— 682	1503	— 427	—.046	9.971
Feb.	2070	2100	9000	2900	1000	5116	—.073	— 681	— 702	1368	— 562	—.060	9.911
Mar.	2014	2100	....	2900	1000	5116	—.039	— 364	— 295	1719	— 211	—.022	9.889
Apr.	2105	2100	....	2900	1000	5116	+.190	+1774	+1843	3948	+2018	+.216	10.105
May	2157	2100	....	2900	1000	5116	+.161	+1502	+1571	3728	+1798	+.193	10.298
June	2239	2100	....	2900	1000	5116	+.396	+3695	+3764	6003	+4073	+.436	10.734
July	2276	2100	....	2900	1000	5116	+.060	+ 560	+ 629	2905	+ 975	+.105	10.839
Aug.	2200	2100	....	2900	1000	5116	+.009	+ 84	+ 153	2353	+ 423	+.045	10.884
Sept.	2148	2100	....	2900	1000	5116	+.046	+ 429	+ 498	2646	+ 716	+.078	10.962
Oct.	2145	2100	....	2900	1000	5116	—.146	—1362	—1293	852	—1078	—.115	10.847
Nov.	2126	2100	....	2900	1000	5116	—.343	—3200	—3131	—1005	—2935	—.314	10.533
Dec.	2108	2100	....	2900	1000	5116	—.202	—1885	—1816	292	—1638	—.176	10.357
Mean	**2148**	**2100**	**1250**	**2900**	**1000**	**5116**	**—.015**	**— 12**	**+ 44**	**2192**	**+ 262**	**+.340**	....
1908													
Jan.	2155	....	6000	3000	1000	6443	—.207	—1932	—1888	267	—1663	—.178	10.179
Feb.	2035	....	9000	3000	1000	6443	—.083	— 774	— 760	1275	— 655	—.070	10.109
Mar.	2085	....	....	3000	1000	6443	+.034	+ 317	+ 421	2506	+ 576	+.062	10.171
Apr.	2225	....	....	3000	1000	6443	+.195	+1820	+1924	4149	+2219	+.238	10.409
May	2282	....	....	3000	1000	6443	+.464	+4330	+4434	6716	+4786	+.513	10.922
June	2284	....	....	3000	1000	6443	+.269	+2520	+2624	4908	+2978	+.319	11.241
July	2240	....	....	3000	1000	6443	+.178	+1660	+1764	4004	+2074	+.222	11.463
Aug.	2196	....	....	3000	1000	6443	—.053	— 495	— 391	1805	— 125	—.013	11.450
Sept.	2107	....	....	3000	1000	6443	—.336	—3135	—3031	— 924	—2854	—.306	11.144
Oct.	1995	....	....	3000	1000	6443	—.295	—2752	—2648	— 653	—2583	—.277	10.867
Nov.	2003	....	....	3000	1000	6443	—.538	—5020	—4916	—2913	—4843	—.519	10.348
Dec.	1956	....	....	3000	1000	6443	—.194	—1810	—1706	250	—1680	—.180	10.168
Mean	**2130**	....	**1250**	**3000**	**1000**	**6443**	**—.566**	**— 439**	**— 348**	**1782**	**— 148**	**—.189**	....
1909													
Jan.	1858	....	6000	3100	1000	6495	—.231	—2155	—2109	— 251	—2181	—.234	9.934
Feb.	1872	....	9000	3100	1000	6495	—.014	— 130	— 114	1758	— 172	—.018	9.916
Mar.	1908	....	....	3100	1000	6495	+.039	+ 364	+ 470	2378	+ 448	+.048	9.964
Apr.	1968	....	....	3100	1000	6495	+.148	+1380	+1486	3454	+1524	+.163	10.127
May	2147	....	....	3100	1000	6495	+.486	+4535	+4641	6788	+4858	+.520	10.647
June	2200	....	....	3100	1000	6495	+.256	+2390	+2496	4696	+2766	+.296	10.943
July	2196	....	....	3100	1000	6495	+.048	+ 448	+ 554	2750	+ 820	+.088	11.031
Aug.	2114	....	....	3100	1000	6495	+.067	+ 625	+ 731	2845	+ 915	+.098	11.129
Sept.	2030	....	....	3100	1000	6495	—.191	—1783	—1677	353	—1577	—.169	10.960
Oct.	1982	....	....	3100	1000	6495	—.359	—3350	—3244	—1262	—3192	—.342	10.618
Nov.	1887	....	....	3100	1000	6495	—.085	— 793	— 687	1200	— 730	—.078	10.540
Dec.	1975	....	....	3100	1000	6495	—.047	— 439	— 333	1642	— 298	—.032	10.508
Mean	**2011**	....	**1250**	**3100**	**1000**	**6495**	**+.117**	**+ 91**	**+ 185**	**2196**	**+ 266**	**+.340**	....
1910													
Jan.	1832	....	6000	3200	1000	6833	—.222	—2054	—2004	— 172	—2102	—.225	10.283
Feb.	1764	....	9000	3200	1000	6833	—.114	—1064	—1044	720	—1210	—.130	10.153
Mar.	1872	....	....	3200	1000	6833	+.012	+ 112	+ 222	2094	+ 164	+.018	10.171
Apr.	1958	....	....	3200	1000	6833	+.276	+2575	+2685	4643	+2713	+.291	10.462
May	2089	....	....	3200	1000	6833	+.173	+1614	+1724	3813	+1883	+.202	10.664
June	2085	....	....	3200	1000	6833	+.096	+ 896	+1006	3091	+1161	+.124	10.788
July	2046	....	....	3200	1000	6833	—.074	— 691	— 581	4465	— 465	—.050	10.738
Aug.	1993	....	....	3200	1000	6833	—.071	— 663	— 553	1440	— 490	—.052	10.685
Sept.	1928	....	....	3200	1000	6833	—.048	— 448	— 338	1590	— 340	—.036	10.650
Oct.	1948	....	....	3200	1000	6833	—.129	—1204	—1094	854	—1076	—.115	10.535
Nov.	1896	....	....	3200	1000	6833	—.303	—2828	—2718	— 822	—2752	—.295	10.240
Dec.	1858	....	....	3200	1000	6833	—.278	—2595	—2485	— 627	—2557	—.274	9.966
Mean	**1939**	....	**1250**	**3200**	**1000**	**6833**	**—.682**	**— 527**	**— 430**	**1509**	**— 421**	**—.542**	....
1911													
Jan.	1800	....	6000	3300	1000	6896	—.294	—2745	—2693	— 893	—2823	—.303	9.663
Feb.	1730	....	9000	3300	1000	6896	+.041	+ 383	+ 405	2135	205	+.022	9.685
Mar.	1757	....	....	3300	1000	6896	—.173	—1615	—1503	254	—1676	—.180	9.505
Apr.	1815	....	....	3300	1000	6896	+.159	+1484	+1596	3411	+1481	+.159	9.664
May	1919	....	....	3300	1000	6896	+.274	+2558	+2670	4589	+2659	+.285	9.949
June	1928	....	....	3300	1000	6896	+.316	+2950	+3062	4990	+3060	+.327	10.276
July	1928	....	....	3300	1000	6896	+.023	+ 215	+ 327	2255	+ 325	+.035	10.311
Aug.	1899	....	....	3300	1000	6896	+.134	+1251	+1363	3262	+1332	+.143	10.454
Sept.	1810	....	....	3300	1000	6896	—.029	— 271	— 159	1651	— 279	—.030	10.424
Oct.	1836	....	....	3300	1000	6896	—.050	— 467	— 355	1481	— 449	—.048	10.376
Nov.	1926	....	....	3300	1000	6896	—.247	—2305	—2193	— 267	—2197	—.235	10.141
Dec.	1878	....	....	3300	1000	6896	+.045	+ 420	+ 532	2410	+ 480	+.051	10.192
Mean	**1849**	..	**1250**	**3300**	**1000**	**6896**	**+.199**	**+ 154**	**+ 257**	**2106**	**+ 176**	**+.226**	....

	I 100 c.f.s.	II c.f.s.	III c.f s	IV c.f.s.	V c.f.s.	VI c.f.s.	VII Feet	VIII 100 c.f.s.	IX 100 c.f.s.	X 100 c.f.s.	XI 100 c.f.s.	XII Feet	XIII Feet
1912													
Jan.	1863	....	6000	3500	1000	6938	—.176	—1641	—1587	276	—1654	—.177	10.015
Feb.	1742	....	9000	3500	1000	6938	—.098	— 915	— 891	851	—1079	—.116	9.899
Mar.	1744	....	....	3500	1000	6938	+.013	+ 121	+ 235	1979	+ 49	+.005	9.904
Apr.	1982	....	....	3500	1000	6938	+.220	+2052	+2166	4148	+2218	+.238	10.142
May	2056	....	....	3500	1000	6938	+.474	+4425	+4539	6595	+4665	+.500	10.642
June	2072	....	....	3500	1000	6938	+.329	+3070	+3184	5256	+3326	+.356	10.998
July	2052	....	....	3500	1000	6938	+.079	+ 737	+ 851	2903	+ 973	+.104	11.102
Aug.	2061	....	....	3500	1000	6938	+.109	+1017	+1131	3192	+1262	+.135	11.237
Sept.	2056	....	....	3500	1000	6938	+.086	+ 803	+ 917	2973	+1043	+.112	11.349
Oct.	2008	....	....	3500	1000	6938	—.215	—2005	—1891	117	—1813	—.194	11.155
Nov.	2037	....	....	3500	1000	6938	—.081	— 756	— 642	1395	— 535	—.057	11.098
Dec.	2006	....	....	3500	1000	6938	—.256	—2389	—2275	— 269	—2199	—.235	10.863
Mean	**1974**	....	**1250**	**3500**	**1000**	**6938**	**+.485**	**+ 377**	**+ 477**	**2451**	**+ 521**	**+.671**	....
1913													
Jan.	2038	....	6000	3700	1000	7839	—.120	—1120	—1054	984	— 946	—.101	10.762
Feb.	2096	....	9000	3700	1000	7839	—.183	—1708	—1672	424	—1506	—.161	10.601
Mar.	2043	....	....	3700	1000	7839	+.133	+1241	+1367	3410	+1480	+.159	10.760
Apr.	2345	....	....	3700	1000	7839	+.592	+5525	+5651	7996	+6066	+.650	11.410
May	2353	....	....	3700	1000	7839	+.310	+2890	+3016	5369	+3439	+.369	11.779
June	2331	....	....	3700	1000	7839	+.159	+1484	+1610	3941	+2011	+.215	11.994
July	2298	....	....	3700	1000	7839	+.068	+ 635	+ 761	3059	+1129	+.121	12.115
Aug.	2189	....	....	3700	1000	7839	+.012	+ 112	+ 238	2427	+ 497	+.053	12.168
Sept.	2065	....	....	3700	1000	7839	—.185	—1726	—1600	465	—1465	—.157	12.011
Oct.	2019	....	....	3700	1000	7839	—.087	— 812	— 686	1333	— 597	—.064	11.947
Nov.	2047	....	....	3700	1000	7839	—.230	—2146	—2020	27	—1903	—.204	11.743
Dec.	2030	....	....	3700	1000	7839	—.153	—1427	—1301	729	—1201	—.129	11.614
Mean	**2154**	....	**1250**	**3700**	**1000**	**7839**	**+.315**	**+ 245**	**+ 360**	**2514**	**+ 584**	**+.751**	....
1914													
Jan.	1973	....	6000	3900	1000	7815	—.239	—2230	—2163	— 190	—2120	—.227	11.387
Feb.	1913	....	9000	3900	1000	7815	—.125	—1165	—1128	785	—1145	—.123	11.264
Mar.	1812	....	....	3900	1000	7815	—.159	—1283	—1356	456	—1474	—.158	11.106
Apr.	1973	....	....	3900	1000	7815	+.137	+1278	+1405	3378	+1448	+.155	11.261
May	2118	....	....	3900	1000	7815	+.334	+3115	+3242	5360	+3430	+.367	11.628
June	2153	....	....	3900	1000	7815	+.244	+2278	+2405	4558	+2628	+.281	11.909
July	2112	....	....	3900	1000	7815	+.133	+1241	+1368	3480	+1550	+.166	12.075
Aug.	2054	....	....	3900	1000	7815	—.057	— 532	— 405	1649	— 281	—.030	12.045
Sept.	2008	....	....	3900	1000	7815	—.110	—1027	— 900	1108	— 822	—.088	11.957
Oct.	1945	....	....	3900	1000	7815	—.122	—1138	—1011	934	— 996	—.107	11.850
Nov.	1948	....	....	3900	1000	7815	—.456	—4255	—4128	—2180	—4110	—.440	11.410
Dec.	1848	....	....	3900	1000	7815	—.288	—2688	—2561	— 713	—2643	—.283	11.127
Mean	**1988**	....	**1250**	**3900**	**1000**	**7815**	**—.708**	**— 551**	**— 436**	**1552**	**— 379**	**— 437**	....
1915													
Jan.	1760	....	6000	4100	1000	7838	—.176	—1642	—1573	187	—1743	—.187	10.940
Feb.	1767	....	9000	4100	1000	7838	+.096	+ 896	+ 935	2703	+ 773	+.083	11.023
Mar.	1808	....	....	4100	1000	7838	—.111	—1036	— 907	901	—1029	—.110	10.913
Apr.	1783	....	....	4100	1000	7838	—.080	— 747	— 618	1165	— 765	—.082	10.831
May	1847	....	....	4100	1000	7838	+.221	+2062	+2191	4038	+2108	+.226	11.057
June	1892	....	....	4100	1000	7838	+.216	+2015	+2144	4036	+2106	+.226	11.283
July	1956	....	....	4100	1000	7838	+.189	+1763	+1892	3848	+1918	+.205	11.488
Aug.	2008	....	....	4100	1000	7838	+.191	+1782	+1911	3919	+1989	+.213	11.701
Sept.	1986	....	....	4100	1000	7838	—.102	— 952	— 823	1163	— 767	—.082	11.619
Oct.	1968	....	....	4100	1000	7838	—.001	— 9	+ 120	2088	+ 158	+.017	11.636
Nov.	1948	....	....	4100	1000	7838	—.213	—1988	—1859	89	—1841	—.197	11.439
Dec.	1870	....	....	4100	1000	7838	—.079	— 737	— 608	1262	— 668	—.072	11.367
Mean	**1883**	....	**1250**	**4100**	**1000**	**7838**	**+.152**	**+ 118**	**+ 233**	**2116**	**+ 186**	**+.240**	....
1916													
Jan.	1980	....	6000	4300	1000	8200	—.127	—1185	—1110	870	—1060	—.113	11.254
Feb.	1980	....	9000	4300	1000	8200	+.042	+ 392	+ 437	2417	+ 487	+.052	11.306
Mar.	1907	....	....	4300	1000	8200	—.027	— 252	— 117	1790	— 140	—.015	11.291
Apr.	2039	....	....	4300	1000	8200	+.391	+3645	+3780	5819	+3889	+.417	11.708
May	2142	....	....	4300	1000	8200	+.554	+5170	+5305	7447	+5517	+.592	12.300
June	2213	....	....	4300	1000	8200	+.536	+5000	+5135	7348	+5418	+.581	12.881
July	2200	....	....	4300	1000	8200	+.158	+1474	+1609	3809	+1879	+.201	13.082
Aug.	2125	....	....	4300	1000	8200	—.144	—1344	—1209	916	—1014	—.108	12.974
Sept.	2052	....	....	4300	1000	8200	—.220	—2052	—1917	135	—1795	—.192	12.782
Oct.	1988	....	....	4300	1000	8200	—.197	—1838	—1703	285	—1645	—.176	12.606
Nov.	1939	....	....	4300	1000	8200	—.018	— 168	— 33	1906	— 24	—.003	12.603
Dec.	1930	....	....	4300	1000	8200	—.181	—1689	—1554	376	—1554	—.166	12.437
Mean	**2041**	....	**1250**	**4300**	**1000**	**8200**	**+.767**	**+ 598**	**+ 719**	**2760**	**+ 830**	**+1.070**	....
1917													
Jan.	1898	....	6000	4500	1000	8726	—.191	—1782	—1700	198	—1732	—.185	12.252
Feb.	1813	....	9000	4500	1000	8726	—.202	—1885	—1833	— 20	—1950	—.209	12.043
Mar.	1868	....	....	4500	1000	8726	+.069	+ 644	+ 786	2654	+ 724	+.078	12.121
Apr.	2035	....	....	4500	1000	8726	+.282	+2630	+2772	4807	+2877	+.308	12.429
May	2151	....	....	4500	1000	8726	+.254	+2370	+2512	4663	+2733	+.293	12.722
June	2272	....	....	4500	1000	8726	+.354	+3302	+3444	5716	+3786	+.405	13.127
July	2355	....	....	4500	1000	8726	+.246	+2295	+2437	4792	+2862	+.307	13.434
Aug.	2289	....	....	4500	1000	8726	—.031	— 289	— 147	2142	+ 212	+.023	13.457
Sept.	2202	....	....	4500	1000	8726	—.128	—1195	—1053	1149	— 781	—.084	13.373
Oct.	2187	....	....	4500	1000	8726	—.249	—2324	—2182	5	—1925	—.206	13.167
Nov.	2164	....	....	4500	1000	8726	—.151	—1408	—1266	898	—1032	—.110	13.057
Dec.	2122	....	....	4500	1000	8726	—.381	—3555	—3413	—1291	—3221	—.345	12.712
Mean	**2113**	....	**1250**	**4500**	**1000**	**8726**	**—.128**	**— 99**	**+ 30**	**2143**	**+ 213**	**+.275**	....

COMPUTATION OF 65 YEAR MASS CURVE (Continued)

	I 100 c.f.s.	II c.f.s.	III c.f.s.	IV c.f.s.	V c.f.s.	VI c.f.s.	VII Feet	VIII 100 c.f.s.	IX 100 c.f.s.	X 100 c.f.s.	XI 100 c.f.s.	XII Feet	XIII Feet
1918													
Jan.	1958	....	6000	4500	500	8826	—.138	—1287	—1209	749	—1181	—.126	12.586
Feb.	1870	....	9000	4500	500	8826	—.113	—1054	—1006	864	—1066	—.114	12.472
Mar.	1982	....	....	4500	500	8826	+.174	+1623	+1761	3743	+1813	+.194	12.666
Apr.	1948	....	....	4500	500	8826	+.163	+1520	+1658	3606	+1676	+.180	12.846
May	1980	....	....	4500	500	8826	+.206	+1922	+2060	4040	+2110	+.226	13.072
June	2043	....	....	4500	500	8826	+.319	+2975	+3113	5156	+3226	+.345	13.417
July	2074	....	....	4500	500	8826	+.048	+ 448	586	2660	+ 730	+.078	13.495
Aug.	2048	....	....	4500	500	8826	—.016	— 149	— 11	2037	+ 107	+.011	13.506
Sept.	2067	....	....	4500	500	8826	—.147	—1371	—1233	834	—1096	—.117	13.389
Oct.	2014	....	....	4500	500	8826	—.199	—1856	—1718	296	—1634	—.175	13.214
Nov.	2057	....	....	4500	500	8826	—.054	— 504	— 366	1691	— 239	—.026	13.188
Dec.	1984	....	....	4500	500	8826	+.013	+ 121	+ 259	2243	+ 313	+.033	13.221
Mean	**2002**	....	**1250**	**4500**	**500**	**8826**	**+.256**	**+ 198**	**+ 325**	**2327**	**+ 397**	**+.509**	....
1919													
Jan.	2085	....	6000	4500	500	8595	—.256	—2389	—2313	— 228	—2158	—.231	12.990
Feb.	2012	....	9000	4500	500	8595	—.097	— 915	— 869	1143	— 787	—.084	12.906
Mar.	2030	....	....	4500	500	8595	+.019	+ 177	+ 313	2343	+ 413	+.044	12.950
Apr.	2151	....	....	4500	500	8595	+.277	+2585	+2721	4872	+2942	+.315	13.265
May	2280	....	....	4500	500	8595	+.313	+2920	+3056	5336	+3406	+.365	13.630
June	2303	....	....	4500	500	8595	+.170	+1586	+1722	4025	+2095	+.225	13.855
July	2248	....	....	4500	500	8595	—.122	—1138	—1002	1246	— 684	—.073	13.782
Aug.	2212	....	....	4500	500	8595	—.157	—1465	—1329	883	—1047	—.112	13.670
Sept.	2130	....	....	4500	500	8595	—.238	—2220	—2084	46	—1884	—.202	13.468
Oct.	2050	....	....	4500	500	8595	—.124	—1156	—1020	1030	— 900	—.096	13.372
Nov.	2065	....	....	4500	500	8595	—.149	—1390	—1254	811	—1119	—.120	13.252
Dec.	1984	....	....	4500	500	8595	—.261	—2435	—2299	— 315	—2245	—.240	13.012
Mean	**2129**	....	**1250**	**4500**	**500**	**8595**	**—.625**	**— 486**	**— 363**	**1766**	**— 164**	**—.209**	....
1920													
Jan.	1798	....	6000	4500	500	8346	—.215	—2005	—1932	— 134	—2064	—.221	12.791
Feb.	1666	....	9000	4500	500	8346	—.093	— 868	— 825	841	—1089	—.117	12.674
Mar.	1698	....	....	4500	500	8346	+.078	+ 728	+ 861	2559	+ 629	+.067	12.741
Apr.	1830	....	....	4500	500	8346	+.408	+3805	+3938	5768	+3838	+.411	13.152
May	1973	....	....	4500	500	8346	+.253	+2360	+2493	4466	+2536	+.272	13.424
June	2030	....	....	4500	500	8346	+.192	+1791	+1924	3954	+2024	+.217	13.641
July	2078	....	....	4500	500	8346	+.179	+1670	+1803	3881	+1951	+.210	13.851
Aug.	2041	....	....	4500	500	8346	+.014	+ 130	+ 263	2304	+ 374	+.040	13.891
Sept.	2008	....	....	4500	500	8346	—.178	—1660	—1527	481	—1459	—.156	13.735
Oct.	1984	....	....	4500	500	8346	—.260	—2425	—2292	— 308	—2238	—.240	13.495
Nov.	1960	....	....	4500	500	8346	—.223	—2080	—1947	13	—1917	—.205	13.290
Dec.	2037	....	....	4500	500	8346	—.197	—1838	—1705	332	—1598	—.171	13.119
Mean	**1926**	....	**1250**	**4500**	**500**	**8346**	**—.042**	**— 32**	**+ 87**	**2013**	**+ 83**	**+.107**	....
1921													
Jan.	1973	....	6000	4500	500	8355	—.166	—1548	—1474	499	—1431	—.153	12.966
Feb.	1915	....	9000	4500	500	8355	—.137	—1278	—1234	681	—1249	—.134	12.832
Mar.	1936	....	....	4500	500	8355	+.023	+ 214	+ 348	2284	+ 354	+.038	12.870
Apr.	2082	....	....	4500	500	8355	+.383	+3575	+3709	5791	+3861	+.413	13.283
May	2145	....	....	4500	500	8355	+.255	+2380	+2514	4659	+2729	+.292	13.575
June	2130	....	....	4500	500	8355	+.112	+1045	+1179	3309	+1379	+.148	13.723
July	2123	....	....	4500	500	8355	—.040	— 373	— 239	1884	— 46	—.005	13.718
Aug.	2042	....	....	4500	500	8355	—.160	—1492	—1358	684	—1246	—.133	13.585
Sept.	2002	....	....	4500	500	8355	—.114	—1064	— 930	1072	— 858	—.092	13.493
Oct.	1925	....	....	4500	500	8355	—.194	—1810	—1676	249	—1681	—.180	13.313
Nov.	1863	....	....	4500	500	8355	—.193	—1800	—1666	197	—1733	—.186	13.127
Dec.	1986	....	....	4500	500	8355	—.185	—1725	—1591	395	—1535	—.164	12.963
Mean	**2010**	....	**1250**	**4500**	**500**	**8355**	**—.416**	**— 324**	**— 201**	**1809**	**— 121**	**—.156**	....
1922													
Jan.	1889	....	6000	4500	500	8358	—.262	—2445	—2371	— 482	—2412	—.258	12.705
Feb.	1767	....	9000	4500	500	8358	—.131	—1222	—1178	589	—1341	—.144	12.561
Mar.	1772	....	....	4500	500	8358	+.095	+ 886	+1020	2792	+ 862	+.092	12.653
Apr.	2039	....	....	4500	500	8358	+.466	+4350	+4484	6523	+4593	+.492	13.145
May	2076	....	....	4500	500	8358	+.473	+4410	+4544	6620	+4690	+.502	13.647
June	2117	....	....	4500	500	8358	+.147	+1371	+1505	3622	+1692	+.181	13.828
July	2090	....	....	4500	500	8358	+.151	+1409	+1543	3633	+1703	+.182	14.010
Aug.	2030	....	....	4500	500	8358	—.020	— 186	— 52	1978	+ 48	+.005	14.015
Sept.	1975	....	....	4500	500	8358	—.104	— 970	— 836	1139	— 791	—.085	13.930
Oct.	1934	....	....	4500	500	8358	—.337	—3145	—3011	—1077	—3007	—.321	13.609
Nov.	1883	....	....	4500	500	8358	—.350	—3265	—3131	—1248	—3178	—.340	13.269
Dec.	1796	....		4500	500	8358	—.357	—3330	—3196	—1400	—3330	—.357	12.912
Mean	**1947**	....	**1250**	**4500**	**500**	**8358**	**—.229**	**— 178**	**— 57**	**1890**	**— 40**	**—.051**	....
1923													
Jan.	1768	....	6000	4500	500	8348	—.103	— 961	— 886	882	—1048	—.112	12.800
Feb.	1703	....	9000	4500	500	8348	—.240	—2240	—2197	— 494	—2424	—.260	12.540
Mar.	1742	....	....	4500	500	8348	+.077	+ 719	+ 852	2594	+ 664	+.071	12.611
Apr.	1823	....	....	4500	500	8348	+.148	+1380	+1513	3336	+1406	+.151	12.762
May	1890	....	....	4500	500	8348	+.331	+3090	+3225	5115	+3185	+.340	13.102
June	1953	....	....	4500	500	8348	+.150	+1400	+1533	3486	+1556	+.167	13.269
July	1915	....	....	4500	500	8348	+.110	+1026	+1159	3074	+1144	+.123	13.392
Aug.	1879	....	....	4500	500	8348	—.080	— 747	— 614	1265	— 665	—.071	13.321
Sept.	1815	....	....	4500	500	8348	—.055	— 513	— 380	1435	— 495	—.053	13.268
Oct.	1772	....	....	4500	500	8348	—.192	—1792	—1659	113	—1817	—.195	13.073
Nov.	1738	....	....	4500	500	8348	—.237	—2210	—2077	— 339	—2269	—.242	12.831
Dec.	1825	....	....	4500	500	8348	—.173	—1614	—1481	344	—1586	—.170	12.661
Mean	**1819**	....	**1250**	**4500**	**500**	**8348**	**—.264**	**— 205**	**— 85**	**1734**	**— 196**	**—.251**	....

COMPUTATION OF 65 YEAR MASS CURVE (Continued)

	I 100 c.f.s.	II c.f.s.	III c.f.s.	IV c.f.s.	V c.f.s.	VI c.f.s.	VII Feet	VIII 100 c.f.s.	IX 100 c.f.s.	X 100 c.f.s.	XI 100 c.f.s.	XII Feet	XIII Feet
1924													
Jan.	1938	....	6000	4500	500	9465	—.179	—1670	—1590	348	—1582	—.169	12.492
Feb.	1755	....	9000	4500	500	9465	+.010	+ 93	+ 143	1898	— 32	—.003	12.489
Mar.	1748	....	....	4500	500	9465	—.105	— 980	— 840	908	—1022	—.109	12.380
Apr.	1857	....	....	4500	500	9465	+.171	+1596	+1736	3593	+1663	+.178	12.558
May	1967	....	....	4500	500	9465	+.247	+2305	+2445	4412	+2482	+.266	12.824
June	1999	....	....	4500	500	9465	+.132	+1231	+1371	3370	+1440	+.154	12.978
July	2045	....	....	4500	500	9465	+.091	+ 850	+ 990	3035	+1105	+.118	13.096
Aug.	1975	....	....	4500	500	9465	+.132	+1232	+1372	3347	+1417	+.152	13.248
Sept.	1918	....	....	4500	500	9465	—.005	— 46	+ 93	2011	+ 81	+.008	13.256
Oct.	1872	....	....	4500	500	9465	—.144	—1344	—1204	668	—1262	—.135	13.121
Nov.	1848	....	....	4500	500	9465	—.391	—3650	—3510	—1662	—3592	—.385	12.736
Dec.	1822	....	.	4500	500	9465	—.299	—2790	—2650	— 828	—2758	—.295	12.441
Mean	**1895**	....	**1250**	**4500**	**500**	9465	**—.339**	**— 264**	**— 137**	**1758**	**— 172**	**—.220**	...
65-Yr. Av'ge	**2087**	**1550**	**1250**	**1670**	**946.**	**2610**	**—.042**	**— 32**	**— 8**	**2079**	**+ 149.**	**+.192**	**0.192**

COMPARISON OF DISCHARGE FORMULA

NOTE: As stated in the foot note on the first page of this table, the values in Column I, for years 1860 to 1907 inclusive, are taken from the report of the International Waterways Commission of 1910. Representative values in this table at various extreme and mean lake heights have been tested by the formula of the U. S. Lake Survey, [$Q=3{,}904\ (\text{Buffalo Gauge}-558.37)^{\frac{3}{2}}$], and by the diagram on page 30, and close agreement found at ordinary heights. Near the extreme top and bottom of the range there are small differences, within the margin of error of measurement.

For example:

	Elevation of Lake Erie at Buffalo	Discharge of Niagara River per Haskell Formula as given in Rept. of 1910	Discharge of Niagara River per U. S. L. S. Formula	Difference Haskell minus U. S. L. S.	Difference Per Cent
	Feet	c.f.s.	c.f.s.	c.f.s.	%
High	574.0	242,700	241,300	+1,400	+0.58
Low	571.0	173,200	175,200	—2,000	—1.14
Mean	572.5	206,000	207,300	—1,300	—0.63

Correction for Ice Obstruction — Column III

A deduction has been made of 6000 c.f.s. for January and 9000 c.f.s. for February, as estimated by Mr. F. C. Shenehon, for the effect of ice in obstructing the flow of Niagara River.

Corrections for Diversions — Columns IV, V and VI.

Additions have been made, for diversions through the Erie Canal, of from 500 c.f.s. to 1000 c.f.s. and for diversions through Welland Canal of from 1000 c.f.s. to 4500 c.f.s., according to date, as per schedule received from Mr. F. C. Shenehon, December 1924. (See pages 350, 351.)

Additions have been made for diversions through the Chicago Drainage Canal amounting to from 2990 c.f.s. to 9465 c.f.s. according to date, as reported by the Engineer of the Sanitary District.

Adjustment of Water Yield for Rise and Fall of Lake Surfaces

The weighted average rise or fall of the four lake surfaces for any one month has been determined by obtaining the difference between the mean elevation of each lake for that month and the previous month and then weighting these differences according to the surface area of the corresponding lake. During January 1860 no change in the elevations of the lakes was allowed for.

LIMITATIONS IN REGULATION

The use of the mass curve proceeds on the assumption that one can safely judge the future by the past. It shows what might have happened if these regulation works, now proposed, had been put into operation 65 years ago.

The purpose of the mass curve, which is shown in the lower zig-zag line of the diagram on page 373, and is plotted from the figures computed in the last column in the preceding table, is to show just when water-storage could have been accumulated, carried over and released, from year to year, under the limitations of lake-height and channel capacity, already referred to on pages 19 to 24 and 228 to 232, for perfect regulation to constant uniform flow.

The mass curve shows there is not sufficient storage capacity available over the Great Lakes after holding these at the highest levels desired for the purpose of increased depth in harbors and shallow channels to store all of the surplus water of flood years. In order to divide in the most equitable manner the benefits of regulation between increased depth for navigation and increased uniformity of flow for power development, it is important to review these limitations in elevation and quantity.

Limits of Heights

(1) The extreme height to which the level of each lake can be raised is limited by the existing conditions and structures all around the harbors of the shores of the Great Lakes; and for the present is taken to be the same as the record high water of 1838. Other records of extreme high water are given in the table on pages 25 and 27, and are shown by the diagram of lake heights following page 198.

(2) A further limitation of high water levels is caused by providing a margin of safety between this extreme high water and the normal high water within which can be held back such extreme sudden inflows from storms, or quick melting of snow, as come only a few times in each century, until the existing natural channel has time to take the surplus downstream. The margin allowed for each lake is shown between the heavy lines on diagram following page 198.

(This margin is largely a matter of judgment, and after experience in operation, may be lessened from the foot now assumed.)

(3) The extreme low limit of lake levels is now fixed by nature in the elevation and shape of channel cross-section controlling the out-flow from each lake.

Records of extreme low water are given on page 25 and are shown by the diagram of lake heights following page 198.

The outlet of Huron has been lowered to a small extent by dredging and scour within the past 35 or 40 years.

The outlets of both Huron and Erie can be lowered in future, if the continued tilting of the region, described on pages 149 to 172, should ever make this important.

(4) The nominal low water level is made higher than extreme low water, to the extent of about 2 feet for the benefit of navigation, by lifting the whole zone of seasonal fluctuation of levels by means of the regulating works, as above described.

This level also is shown by a heavy line on the diagram of lake heights following page 198.

(This nominal low water line, also, is subject to change after experience, and on rare occasions — perhaps for a month or two or once in 10 years—may be under-run.)

Some of these data useful in connection with problems of regulation has been assembled in tabular form in the following pages for convenience of reference.

Once more the writer would make plain that the same range of rise and fall for storage, and the same mass curve computations will apply if flowage planes are made a foot lower and channels dredged a foot deeper.

Available Range in Increased Depth of Each Lake and Weighted Average Depth for All

	Range, Extreme Low to Normal High					Normal Range			Proposed Margin of Safety	
	Normal High	Extreme Low	Depth of Draft	Area Billion sq. ft.	Contents Billion cu. ft.	Normal Low	Normal Draft	Billion cu. ft.	1838 Margin ft.	Billion cu. ft.
Superior	604.5	600.54	4.0	8,870	35,480	602.0	2.5	22,200	0.82	7.280
Michigan-Huron	583.5	578.25	5.25	12,660	66,460	581.0	2.5	31,650	1.19	15,050
Erie-St. Clair	574.5	570.5	4.0	2,900	11,600	573.0	1.5	4,350	0.61	1,770
Totals				24,430	113,540			58,200		24,100
Weighted averages of depth of draft in all lakes			4.65 ft.				2.38 ft.		0.99 ft.	

The above table shows that under the proposed limitations there is **available for storage and regulation purposes an average depth of only 2.38 ft. between normal high and normal low water.**

Between extreme low and normal high the range is 4.65 feet, while by temporary extension to record high water of 1838, there would be added a mean depth of 0.99 ft., making the entire range from extreme low water to high water of 1838 equal to 5.64 ft.

In other words, in order to benefit navigation by increased depth of draft, it is proposed to sacrifice more than half of the range in height that otherwise would be available for making the discharge uniform.

Limits of Discharge

(5) Under present conditions, the possible rate of flood discharge is limited by depth and width of lake outlets to about 279,000 c.f.s. for Huron-Michigan at elevation 584.69 (H. W. 1838), and to about 267,000 for Erie at Elevation 575.11 (H. W. 1838).

(**This can be increased by deepening and widening these outlets, which can be done safely at relatively low cost, and with great benefit to future increased depth of navigation, after the regulation works are in service.**)

This work is still a long way off, and no precise estimates or designs are now presented.

At Lake Superior the sluice gates now control the discharge. Prior to their construction the discharge through the St. Marys River, with Lake Superior at the record high water of 1838 (Elev. 605.32), would have been about 143,000 c.f.s., according to an extension of the discharge diagram by the formula of 1898.

It is understood that the power canals can aid materially in carrying off an excess of flood water.

(6) The rate for regulated minimum discharge for Niagara in the earlier years is proposed at 180,000 c.f.s. for the annual average, with 190,000 or 200,000 in summer, and 170,000 or 160,000 c.f.s. in winter.

The mass curves indicate that after lake levels have been raised and experience has been gained in operation, an average annual discharge of about 190,000 c.f.s. may be maintained, with always about 200,000 c.f.s. in summer, and about 180,000 in winter. At the outlet of Huron the discharge in winter may be cut down to the quantity which will pass through the open fairway while all sluice gates are closed. This will impose no greater limitation in rate of discharge than has heretofore been imposed by ice-jams in severe winters.

The engineers in charge of channel improvements about the Great Lakes are understood to have given much attention to placing the spoil from the more recent excavation in Livingstone Channel, back in the river, so that this enlargement would not lower the water levels above. Obviously, as soon as regulation works are available on the Huron outlet it will be far better to place such spoil outside the water way, and give the most free discharge for waters from a great flood.

The regulating gates have been given particularly generous opening in anticipation of the future radical enlargement of the "bottle necks" at the outlets of Lake Huron and Lake Erie. It costs very little more to provide for the very best of future improvements at the present time, although 20 or 40 years may elapse meanwhile.

Attention is again called to the better control of regulation that could be obtained by limiting the width of open fairway throat to not exceeding 250 feet or 300 feet.

A study of the diagrams of average monthly heights of each lake, following page 198 in connection with the diagram on page 235, showing average quantity discharged from each lake month by month, shows year by year a rise seldom or never less than 1.0° F. or greater than 1.5 ft., from January to July, and a corresponding fall from August to December. Naturally, the ups and downs of the discharge diagram must follow closely upon the diagram of lake heights, because the discharge is controlled by the height of lake. Thus the discharge from Lake Erie through the Niagara River commonly has been about 20,000 c.f.s. smaller in January than in July, but in some years this range between high and low discharge, in course of a single year, has been over 50,000 c.f.s.

Under the proposed future regulation the change will be made by steps near the beginning and end of the navigation season, instead of a slow and steady increase to the high peak in August and to a low point about February 1.

From January to April the discharge through the St. Clair River that would naturally result from a given height in Lake Huron, may be largely modified by ice which may cover more or less of the 80 miles of channel between Lakes Huron and Erie, and by ice-jams, which, on rare occasions, cut the flow down to one-third of its normal volume. The St. Clair River line on the discharge diagram on page 235 shows that in many winters ice-jams serve much the same purpose in holding back the winter flow, and storing it for use during the following summer, that would result from the future operation of the proposed regulating gates.

VARIOUS KINDS OF REGULATION

The design of the proposed regulation works in the St. Clair and Niagara Rivers has been made flexible so that their operation can be adjusted to any desired program of lake levels or discharges. By means of adding from one to three feet to the height of structures shown in these drawings, the gates can hold the elevations of lake surface up to the standard high water plane of 1838; or can let it fall as low as the natural notch in the rim of the basin will permit while carrying the minimum flow of river. Therefore, any one of many programs of regulation can be tried out, and changed after trial, to meet changed ideas or future changes in conditions. By means of these works, as now proposed, the lakes could be held either at constant high water, or so as to give a constant rate of discharge or adjusted to any desired subdivision between.

By varying the rules for operation, either navigation or power development could be favored, as conditions may require from time to time, but in the examples presented, the purpose has been to divide the benefits fairly, and so as to give in general about two or three feet greater depth for navigation in cycles of low rainfall than could be had without regulation works, while at the same time adding about 20,000 c.f.s. to the minimum flow of dry years, by the release of stored water from Lakes Superior, Michigan and Huron, drawing each of these lakes down to a depth below the new working high water level not much greater than the present lowering in elevation of lake surface from August to February in each year, which is about one foot, or sometimes a foot and a half.

In other words, **it is proposed by means of these regulation works to lift the whole zone of lake level fluctuation from winter to summer about 2 feet above the elevations at which they have averaged in the past under natural conditions.**

When the low water level is thus raised, and normal high water is held down to average about 1.0 ft. below the high water of 1838, so as to give a generous margin of safety for extreme floods, there does not remain sufficient storage capacity between normal high and normal low to store all of the surplus water of flood years and some must be wasted.

In Lake Erie the depth of storage ordinarily withdrawn, as shown on diagram on page 383, is proposed to be made somewhat less than for the lakes farther upstream, keeping Erie high for the two purposes of improvement in navigation depths throughout Lake St. Clair, and for the convenience of having an ample volume of water in storage close to Niagara Falls, for emergency release, for either scenery or power.

Following the installation of gates in both the Niagara and St. Clair Rivers, a first thought on regulation might be to operate for constant maximum height, which could be obtained by simply closing these regulating gates more or less until the water had risen to the nominal high water level, and then open and adjust the gates from week to week, so as to cause the outflow to equal the inflow (less evaporation loss), and thus always maintain the lakes at this nominal high water level. Although such a course would maintain the best possible conditions for navigation, it would unfortunately give a rate of flow much more irregular than that under present conditions, and this increased irregularity would be much less satisfactory for scenic purposes and for power development at Niagara; and possibly would involve trouble from excessive flood heights, following heavy rains like those which caused the great Ohio floods during March 23–27, 1913.

A second scheme for regulating might be that for constant uniform discharge, obtained by first closing the gates until the lake levels are wholly restored to normal high water in July, then opening the gates at the outlets of Huron and Erie more and more as the natural yield of the water declined, so as to maintain a constant flow in the Niagara River of, say, 200,000 cu. ft. net, after allowing for diversions, which quantity is but little less than the average rate of discharge found by gagings for the past 25 years.

The trouble with this scheme is that by maintaining the discharge at so high a rate throughout a cycle of dry years, the lake levels would be gradually drawn down to the low levels at which they now stand, or injuriously low for navigation, and the raising of the lake levels would have to await the return of a cycle of years of large rainfall.

The proposed raising of the low water level two or three feet above its present natural and injurious minimum, for the benefit of navigation, while also obtaining the uniformity of flow desirable for future development of power, compels that a compromise be made at the sacrifice of storage and a decrease in the possibility for larger regulated flow; because flowage damages would prevent lifting the high water level as far as it is desired to lift the low water level.

It may be of interest to follow the steps by which the present compromise was reached.

CONSTRUCTION OF MASS CURVE NO. 1

The diagram on the next page is a copy, reduced to a scale one-sixth of the original diagram worked out on a sheet of cross-section paper 43 inches in length and 26 inches in height. Although this small copy lacks the precision necessary in a working chart, it will serve to illustrate the methods.

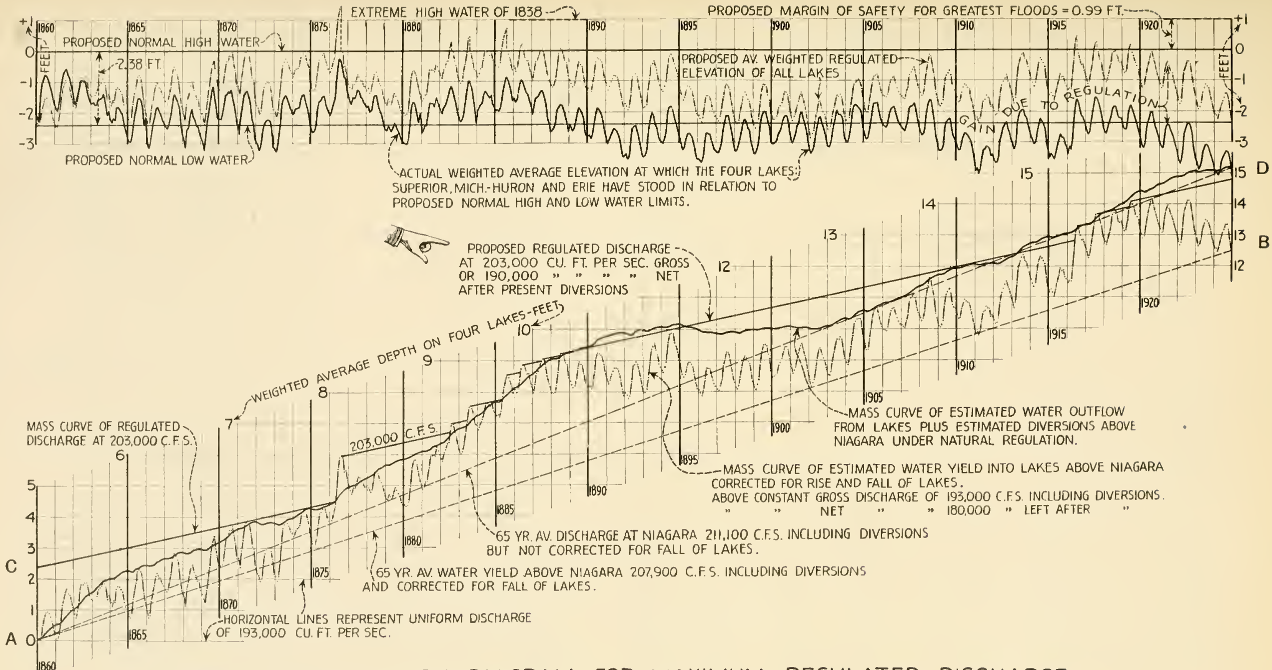
The horizontal spaces on this mass diagram measure off the years and months. The vertical spaces measure off the successive monthly totals of the mass curve computation given in the last column of tables on pages 354 to 366 in which the cumulative surplus from month to month, over and above a constant draft of 193,000 c.f.s. gross (or 180,000 c.f.s. after diversion), is measured in terms of weighted average depth of storage in all of the lakes upstream from Niagara.

The zig-zag line of accumulated quantity follows a course somewhat similar to that of the zig-zag lines of lake elevation, in the diagram following page 198, which several lines of lake elevation also are the result of similar activities by Nature in accumulation of storage and release. The natural line results from a rate of discharge which constantly varies with the height in the lake, whereas this tabular computation assumes an unvarying discharge of 193,000 c.f.s.

It is of interest to note within the length of this mass diagram two distinct cycles of change in rate of water yield. For the first 27 years the line of yield rose at a rapid rate culminating in 1888, after which the zig-zag line of accumulation rises at a less rapid rate, until 1902, after which it again rises more rapidly and reaching its summit in 1919, and since then falling rapidly to the present time.

After having traced out the mass curve, the first problem is to find what amount of storage would be required for the complete control and production of an unvarying discharge of about 207,900 c.f.s.; which is the actual corrected average gross water yield of all of the lakes upstream from Niagara for the past 65 years.

First, drawing a straight line (AB) from the beginning to the end of the zig-zag line, this is found to rise 12.441 ft. within a period of 65 years, which is at the rate of..........0.1914 ft. per year.



MASS CURVES AND DEPLETION DIAGRAM FOR MAXIMUM REGULATED DISCHARGE (190,000 CU. FT. PER SEC. NET) AT NIAGARA FALLS

This depth multiplied into the area of all the lakes of 86,720 sq. miles is equivalent to 466 billion cubic feet and divided by the number of seconds in one year is equivalent to a discharge of 14,900 c.f.s. which added to the 193,000 c.f.s. gross draft of the base line gives a mean discharge of...207,900 c.f.s. In other words, this straight line (AB) represents the mass curve which would have resulted from a constant net inflow at rate of 207,900 c.f.s. and checks with the numerical average of the preceding table.

This period of 65 years happens to have begun with a succession of years of more than average water yield, presenting first a long period of accumulation, and later a period of withdrawal from storage.

The vertical distance above this straight line (AB) to the zig-zag mass line, measured at any year or month shown on the horizontal scale, gives the excess depth of water that could have been stored up to that time, had there been space for it, while maintaining a constant uniform draft of 207,900 c.f.s.

Surplus could have gone on accumulating in storage from 1861 until 1888, after which storage would have declined until 1903; then, would have risen until 1908; then, decreased until 1911; then, risen until 1919, presenting then a full reservoir; and after that time, again gradually declined to the present stage in 1924.

The maximum of surplus depth in storage would have been accumulated at August 1887, amounting to a weighted average for all the lakes of 3.8 feet. Since it happened that at the starting point in January, 1860, the Great Lakes were at about normal low water, the available storage depth from which level to normal high water is only 2.38 feet, to have retained all of this 3.8 feet average rise, without at any time increasing the discharge beyond this average of 207,900 c.f.s., would have carried the lake levels up more than a foot above the practicable limit of high water.

If the lakes had happened to stand in the beginning of the mass curve, as now, at about extreme low water, the available storage depth of 4.65 feet between extreme low and normal high lake levels could have retained all of this yield while maintaining 207,900 c.f.s. outflow; but navigation would have suffered from scant depth while waiting 16 years from 1860 to 1875 inclusive; and again, while waiting for a rise during most of the 20 years from 1896 to 1915.

If the lakes had been filled to the new normal high water level at the beginning in 1860, frequent waste of surplus would have been required, and from these diagrams it is plain that working under these limitations a lower rate of continuous draft ....than 207,900 c.f.s. must be adopted.

The resulting depletions are shown more plainly perhaps in the corresponding diagram above the mass curve on page 373, and plainly **represents the largest possible degree of conservation, and storage, and resulting uniformity of flow obtainable from a repetition of the average weather conditions of the past 75 years, and is the ideal to be worked for in the design of regulating works,** although it may not be found expedient to apply precisely this schedule within the next 10 or 20 years, or 40 years, or until the narrow gorges at outlets of Huron and Erie have been widened, or until the demands for water power along the Niagara and St. Lawrence Rivers have become largely increased.

The Maximum Practicable Constant Rate of Draft

In general, the most convenient way to use the mass curve is by drawing the trial lines for rate of draft between peaks on the mass curve; and from the divergences thus found, making a separate diagram showing the depletions month by month and year by year resulting from various rates of draft from a reservoir full at the start.

Assume a constant rate of draft of............................203,000 c.f.s. gross, which, after diverting 13,000 c.f.s. into Chicago, Welland and Erie Canals, is equivalent to a net flow in upper Niagara River of..190,000 c.f.s. or if the Chicago diversion is 4,167 c.f.s. this becomes about..195,000 c.f.s.

And assume that in order to avoid waiting for years of larger rainfall and smaller evaporation, that gates are closed to greatest practicable extent immediately after completion of the construction of the regulating works, and that the levels of all lakes are raised as quickly as practicable to the newly prescribed normal low water level at 2.4 feet below the prescribed normal high water. Although this average annual rate of 190,000 c.f.s. net would be varied from say, 200,000 c.f.s. in the navigation season, to 175,000 c.f.s. in winter, this variation need not be noted on the diagram so long as the total draft for the year remains the same, or equivalent in total amount to a constant draft of 190,000 c.f.s. Therefore the line may be drawn at the constant net rate of draft of 190,000 c.f.s.

The straight lines (CD), representing 203,000 c.f.s. continuous draft, rising on the scale of this diagram at 0.1286 feet per year above the base rate of 193,000 c.f.s., and with reservoirs touching normal high level in 1871, encounters in 1876 the greatest rate of inflow known in 75 years, necessitating opening all sluice gates wide from April until nearly the end of the year, and so over-taxing present channels that if such a flood came prior to enlargements of the "bottle-necks" at Port Huron and Buffalo, all lakes would have been raised for a brief period to about the high water level of 1838. No other such severe test has occurred within 100 years, and it may not occur for another 100 years. Extreme flood yields will be discussed further, on a later page.

Continuing to follow along this trial line and mass curve, the next 3 years, 1877–78 and 79, were years of small water yield, and reservoirs would not become refilled until 1882, when a slight surplus would be wasted, as also in 1883–84–85–86–87–88, all of which were years of large yield.

Then follow 5 years of small yield, in which storage would be drawn down, but an increased yield occurs in following years so that the reservoirs become almost completely refilled in 1895; after which no surplus would require discharge during 21 years, or until 1916.

Meanwhile storage of previous years would have been drawn, and reservoirs depleted to their maximum in 1902 and 1911.

But even in these extreme years, the average height in Huron-Michigan and Erie during the navigation season would have been a foot higher than under natural control.

And, meanwhile, the discharge for scenery and power would have averaged 190,000 c.f.s., instead of averaging in one year (1895) only 166,000 c.f.s. The gain due regulation is 24,000 c.f.s.

The reservoirs would have overflowed slightly in 1916, 1917, and 1919. And in 1924, throughout the navigation season, all lake levels would have averaged slightly above the new normal low water levels, and 1 8 feet higher than they actually stood.

EFFECT OF NATURAL REGULATION

While on the subject of mass curves, it is interesting to note the change in rate of yield in one long period as compared with another, and the excess or deficiency as compared with the regulated average gross water yield of 207,900 c.f.s.

Period	Measured Gross Yield in Upper Niagara River Corrected for ice Corrected for diversions Corrected for rise or fall of lakes
5 years — 1855 to 1859 — prior to period ordinarily considered and for which data may be less accurate	259,500 c.f.s.
26 years — 1860 to 1885 — High cycle	216,700 c.f.s.
17 years — 1886 to 1902 — Low cycle	196,300 c.f.s.
16 years — 1903 to 1918 — High cycle	214,900 c.f.s.
6 years — 1919 to 1924 — Low cycle, incomplete,	182,800 c.f.s.

Some of the extremes of average annual water yield within this period show a much wider departure than the examples above, from the average of 207,900 c.f.s.

A SECOND AND MORE CONSERVATIVE MASS CURVE

The mass curve shown in the diagram on page 373, and described in the preceding pages, was devised to show the utmost steady flow that could be obtained within limits of rise and fall, between nominal low water and nominal high water, amounting to 2.5 feet in the case of Lakes Superior, Michigan and Huron, and 1.5 feet in the case of Lake Erie.

As previously stated, this range of 2.5 ft. and 1.5 ft. in height could be obtained either by maintaining the high and low water of the several lakes respectively at elevations 604.5–602.0 for Superior, 583.5–581.0 for Michigan-Huron, and 574.5–573.0 for Lake Erie, or this stated amount in range from high to low could be obtained with high water reduced one foot, or two feet, below those elevations just stated, if navigation channels and harbors were dredged deeper to an equal amount.

In this first mass curve it was assumed that if normal high water was fixed at the highest level stated, and if the lakes were forthwith brought up to these high levels, that prior to the time of enlarging the narrow "bottle necks" at the outlets of Lake Huron and Lake Erie, there might once or twice in a century be lake levels, caused by great rainfalls, that would rise higher than this nominal highwater and which would encroach more or less upon the safety zone provided between nominal high water and the flood levels of 1838.

The second mass curve (see page 381) accepts as the regulated nominal minimum constant flow, 193,000 c.f.s., a quantity 10,000 c.f.s. smaller than provided for by the first mass curve, this reduction being made chiefly for the purpose of lessening the possibilities of high water and for lessening the length of periods of depletion.

This second mass curve if in use during the past 60 years would at no time (except possibly in 1876) have necessitated any encroachment within this "safety zone" between nominal high water and the recorded high water of 1838.

This precaution against high water, is maintained by means of a schedule of operation carefully devised in advance, under which, whenever it is observed that the lakes are tending to rise to greater height than ordinary, or whenever there are large accumulations of snow or other indications of flood, the regulation gates in the St. Clair River and at Niagara all would be opened wide, one month, or perhaps two months, **prior to the coming of the peak of the flood,** thereby preventing rise beyond the nominal high water limits.

The regulating gates, both at Niagara and in the St. Clair River, have been designed with a surplus capacity such that quantities larger than 250,000 c.f.s. can be discharged after the narrow throats which now control the outflow from Lake Huron and Lake Erie have been enlarged.

Trial estimates were made for various schedules, and that now presented was adopted tentatively, after finding that this would have accomplished the purpose desired in each and all of the floods and high lake levels of the past 65 years.

For simplicity of computation, the openings of flood gates were estimated in two capacities or groups for emergency work; in the first of which the openings would be increased so as to discharge 20,000 sec. feet of surplus above the normal regulated flow of 180,000 c.f.s.; and in the second group 50,000 c.f.s. additional, thus providing during as many days or months as required, a total waste of surplus flow amounting to 70,000 c.f.s. over and above the normal discharge of 180,000 c.f.s. at Niagara.

This second mass curve and this schedule are the same that was presented in part in the preliminary report of the Board of Review, dated January 23, 1925, in diagram following page 80.

In the present report the diagram covering 65 years from 1860 to 1924 has been cut into halves, and one half, comprising the 33 years from 1860 to 1892 placed at the top of the page, and the other half comprising the period 1893 to 1924 placed in the lower half of the page.

Within the past 30 years and particularly within the past 25 years, the water stage gages have been looked after more carefully, and the estimates of discharge are probably more accurate than in the earlier years. Nevertheless on comparing the two halves of the mass curve and of the depletion diagram that accompanies it, shown by the shaded serrated line, very little difference is found. In other words, the history of one 30-year period is closely repeated in that of another 30-year period; and going back still further to the records of lake heights 100 years ago presented on page 27, the evidence is all concurrent to the effect that no great climatic change has been going on during the past century, by which the supply of water in or from the Great Lakes is diminishing.

Coming now to a description in detail of the lines in what are virtually three separate diagrams on the following page,

(1) The mass curve

(2) The depletion diagram

(3) The diagram of waste of surplus.

The zigzag line in the mass curve represents the water yield from all of the Great Lakes combined, after correcting this for the rise and fall of each lake month by month.

In order to lessen the height of the diagram and permit a larger and more open scale, a deduction has been made from each monthly quantity amounting to 193,000 c.f.s. so as that the line is plotted showing the accumulating surplus over and above this quantity of 193,000 c.f.s. which is the regulated uniform flow composed of 180,000 c.f.s., plus 13,000 c.f.s., which is the sum of the diversions now being made at the Chicago Canal, the Welland Canal and the Erie Canal.

The thin straight broken line between points 5 years apart, has been drawn to make clear the variations of water yield within cycles 5 years in length.

The dash line at the top, shows when level that the yield into the lakes within the period covered, is all being utilized for maintaining the nominal outflow at Niagara at the uniform rate of 180,000 c.f.s.

Wherever this dash line rises, it indicates that a surplus yield is coming into the lakes which must be wasted through opened sluice gates, as indicated by the steps in the diagram at the top, which show flood discharges at the temporary rate of either 20,000 second feet or 70,000 second feet, above the uniform rate of 180,000 c.f.s.

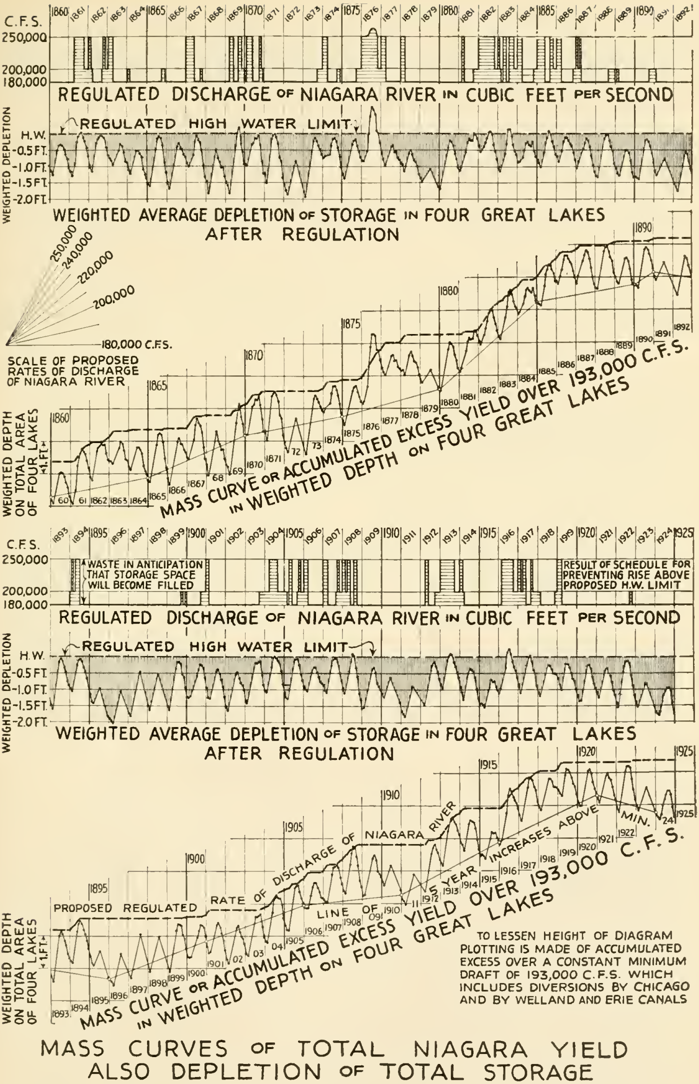
The middle serrated shaded diagram, shows the weighted average depletion of storage in all four lakes year by year, resulting from the uniform draft of 180,000 c.f.s. draft at Niagara, and the surplus discharges of 20,000 and 70,000 c.f.s. during flood periods shown on the diagram above.

It is of particular interest to note by means of this depletion diagram that **for more than 55% of all the time, within the navigation season that the lake levels would never fall more than half a foot below the regulated high water level,** and that for 14% of all the time in the navigation season they would be always less than one foot below regulated high water, and that the extreme depletion outside the navigation season, save in the single year of 1896, would have never been more than 1½ feet below the regulated high water.

The nominal low water of El. 602.0 in Superior, El. 581.0 in Michigan-Huron, and El. 573.0 in Erie would have been touched only once in 65 years.

The depletion diagram that accompanys the mass curve on the following page presents a combination or weighted average of the depletion effect in all of the Great Lakes.

On page 383 is presented a somewhat similar diagram, corresponding to this second and more conservative mass curve, in which the effects of regulation instead of being combined, is separated into the several amounts appropriate to the different lakes.



MASS CURVES OF TOTAL NIAGARA YIELD
ALSO DEPLETION OF TOTAL STORAGE

A sample schedule of operation such as can safely be worked out in advance is shown in the following table.

TENTATIVE REGULATING SCHEDULE—A

Conditions

In addition to mean Chicago Diversion, for 25 years (1900–24) =6,795 c.f.s.

In addition to 3,000 c.f.s. for locks in Welland and Erie Canals equivalent to 4,500 c.f.s. for 8 months of navigation season (April 1–December 1).

(1) Maintain Niagara River flow **in summer** (Navigation and Tourist months, May to October inclusive) at .... 190,000 c.f.s.

(2) Maintain Niagara River flow **in winter** (Non-navigation and non-tourist months, November to April inclusive) at .... 180,000 c.f.s.

(3) Close all Regulating Gates in St. Clair River November 1st. Let Lake Erie draw down, not below El. 572.0, before Feb. 1.

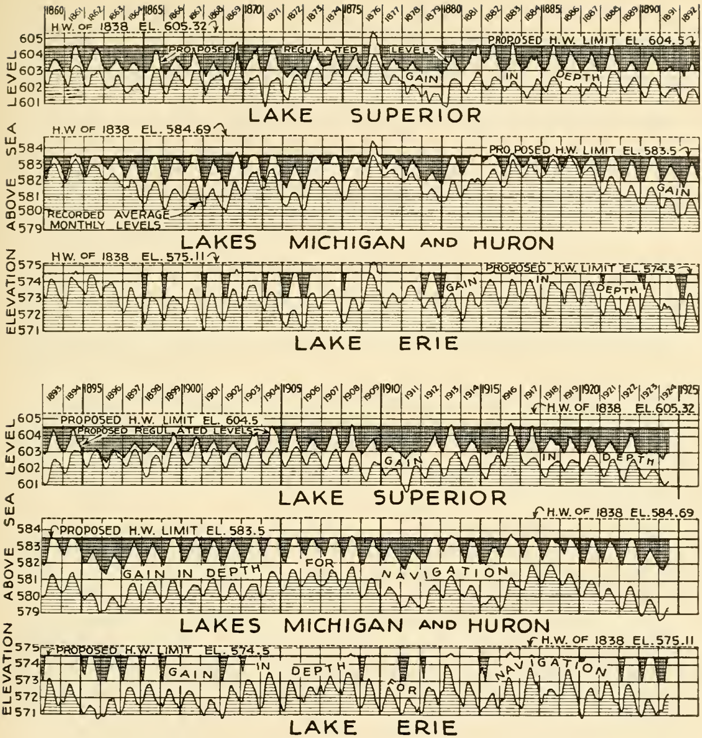
(4) Open wide Regulating Gates in St. Clair River in April so far and so long as is needed to raise Lake Erie to El. 574., or El. 574.5 before June 1st.

Month	Draft from Lake Erie for Niagara River plus 5,000 c.f.s. for navigation April 1–Dec. 1	Yield from Lake Erie and Lake St. Clair water-shed		Desired regulated flow thru St. Clair River to hold Lake Erie at constant elevation	Natural un-regulated monthly discharge of St. Clair River 25-yr. mean 1900–1924	Quantity that will discharge thru St. Clair River due to limits of regulation and ice	Excess that cannot be held back by regulating works or ice but can be used to aid in filling Lake Erie when down
		Per cent of 25-yr. mean of 25,800 c.f.s.	Equivalent yield in cu. ft. per sec.				
	c.f.s.	%	c.f.s.	c.f.s.	c.f.s.	c.f.s.	c.f.s.
Jan.	180,000	172	44,200	135,800	140,600	135,800	0
Feb.	180,000	166	42,800	137,200	124,700	137,200	0
Mar.	180,000	213	54,900	125,100	154,400	*127,000	1,900
April	184,500	380	98,000	86,500	174,500	*128,500	42,000
May	194,500	220	56,600	137,900	189,900	137,900	0
June	194,500	160	41,100	153,400	195,400	153,400	0
July	194,500	65	16,800	177,700	197,600	177,700	0
Aug.	194,500	—20	—5,100	199,600	197,100	199,600	0
Sept.	194,500	—61	—15,700	210,200	194,300	210,200	0
Oct.	194,500	—75	—19,300	213,800	190,400	213,800	0
Nov.	184,500	—70	—18,000	202,500	186,700	202,500	0
Dec.	180,000	50	12,800	167,200	173,300	167,200	0
Mean	188,000	100	25,800	162,200	176,570	165,900	3,700

*Minimum limit of regulation due to size of Fairway.

Between November 1st and May 1st do not open any of the St. Clair gates (in addition to the fairway) unless Lake Erie has dropped more than Lake Huron below their respective H. W. levels or unless schedule calls for a Niagara discharge of more than 200,000 c.f.s.

Between May 1st and November 1st throttle the Niagara discharge (below the maximum 250,000 c.f.s.) if necessary to **maintain Lake Erie** at H. W. El. 574.5.



INCREASED DEPTH FOR NAVIGATION
GAIN FROM NATURAL TO REGULATED LEVELS

The diagram above shows how the depletion of storage caused by an average annual draft of 193,000 c.f.s., so regulated as to give a minimum winter flow of 180,000 c.f.s. and a summer flow of 190,000 to 250,000 c.f.s. in the Niagara River, as determined from the second mass curve, on page 381, could have been distributed over the four lakes, Superior, Michigan, Huron and Erie.

It also shows the increased depth on each lake that could have been obtained for navigation from the actual water yields of the past 65 years, by the regulating works now proposed.

In this diagram showing increased depth for navigation, as in the second mass curve, the period of 65 years is cut near the middle, and the earlier half shown at the top, and the later half of the period near the bottom of the page.

For each of the lakes, the bottom serrated line with horizontal shading, shows the present range in elevation of the unregulated height, up and down month by month in each lake, as recorded by the gages during the past 65 years.

The upper serrated line, distinguished by cross line shading, shows the amount of depletion below the proposed nominal high water that would have occurred in each lake in each year and month during the past 65 years, if the regulation works now proposed had been in place and operated under the conservative schedule shown on the preceding page, maintaining at all times, winter and summer, never less than 180,000 c.f.s. per second at Niagara, and in periods of surplus flow wasting up to discharges of 250,000 c.f.s. all water that could not be held in storage without raising the flowage levels to an objectionable height, meanwhile also maintaining the summer flow at not less than 190,000 c.f.s.

The white or unshaded space between these two zigzag lines, shows the gain in depth in each lake, for purposes of navigation.

In Lake Erie it will be noted that continuously for 7 years, from 1915 to 1923, the lake levels could have been maintained at the nominal high water at substantially at all the times within the navigation season; and at no time within the 65 years would Lake Erie have been drawn more than about one and one-half feet below high water.

In the case of Lakes Michigan and Huron, the gain in depth during the past few years of extreme low water would have been about 3 feet throughout the navigation season, and for the entire period of the past 25 years, the gain would have been between 2 feet and 2½ feet.

In Lake Superior the gain would have been about one foot, assuming that this lake level could have been held up to a nominal high water limit of El. 604.5 by the existing regulation gates near the Sault Locks.

Apparently, the power canals on the Michigan side and the Canadian side both afford special facilities for providing against the water rising too high; since by opening their present gates or by providing additional gates in these power canals, the maximum flow down the rapids, from opening wide the regulation gates of the Stoney type, can be supplemented to the extent of upward of 50,000 c.f.s.

DISCHARGE OF GREAT FLOODS

Consideration must be given to the possibilities of flowage damage which might be caused by a severe flood happening to come during one of those rare occasions (about twice in 60 years), when all of the lakes or rivers would be completely full, if operating under the first mass curve for maximum conservation.

Under the theory of probabilities this coincidence of a heavy flood on top of a full reservoir is extremely remote.

If such flowage is feared, the most obvious precaution is to defer raising the flowage limit of normal high water up to the full final height proposed on page 230 until after the "bottle necks" or narrow gorges which control the outlets from Lake Huron and Lake Erie have been enlarged.

The capacities for discharging flood water at the outlets of the several lakes when at their maximum heights are as follows:

Name of Lake	Elevation of Normal High Water	Discharge at Normal High Water	Elevation of High Water of 1838	Discharge at 1838 Level
LAKE SUPERIOR This now has control gates. Prior to gates the natural river gave this discharge	604.5	128,700	605.32	143,000
The power canals can now add to this discharge probably upward of	——	50,000+	——	50,000+
LAKES MICHIGAN-HURON... (By Harbor Beach gauge)....	583.5	255,000	584.69	279,000
LAKE ERIE (By Buffalo gauge)	574.5	253,000	575.11	267,000
LAKE ONTARIO (By Oswego gauge Since the construction of Gut Dam in 1903	......	......	548.98	303,500

The above indicates that all along the line a discharge of upward of 250,000 c.f.s. can be carried at normal high water, through these narrow gorges at Port Huron and below Buffalo as they now stand.

To increase the width and enlarge their capacity gradually to the extent of, say, 25 per cent, would seem reasonable, being perhaps 20 years hence. The designs proposed contemplated making this enlargement before attempting full conservation or storage to this normal high water.

The great area of the lakes in proportion to the land area, and the apparent sluggish delivery from these water sheds are a great safeguard.

The following table shows the most excessive inflows that have occurred within the past 70 years, and that these have been taken care of naturally without noteworthy damage.

A flood following a great rain culminates and passes down the river and into the lakes within one or two weeks.

Daily records have not yet been searched for floods.

The equivalent of the greatest flood recorded in these 70 years, even within a month, is found to have raised the lakes but a few inches.

The most rapid rise found in one month has been 1.58 feet on Lake Erie, from March to April, 1913.

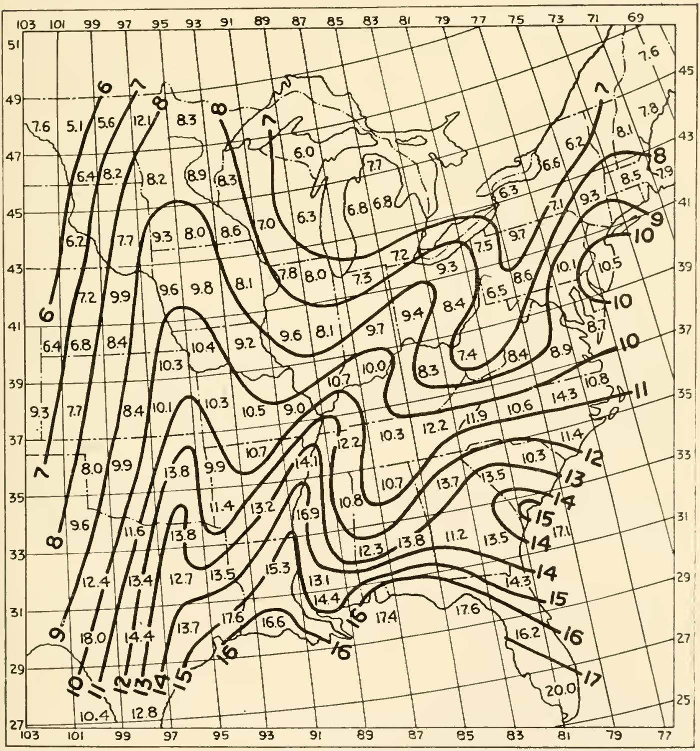
PERIODS OF MOST RAPID YIELD FROM WATER SHED INTO LAKE ERIE FOR A SERIES OF YEARS

1873, 1876–1877, 1882–1885 and 1904–1907

These yields have been computed during months of spring flood during these periods by adding the excess of inflow over outflow, plus correction for rise of lake.

	1 year	3 years	6 years	4 years
	1873 only c.f.s.	1875 to 1876 inc. c.f.s.	1880 to 1885 inc. c.f.s.	1904 to 1907 inc. c.f.s.
Average annual yield for period...		260,700	239,400	221,700
Maximum mean annual yield.....	295,700	(1876) 293,000	(1881) 268,700	(1904) 242,200
Largest total monthly net water yield of 4 lakes exclusive of evaporation but including outflow, recorded during above periods.				
March..........	345,500	(1876) 432,600	(1882) 423,300	(1904) 362,700
April..................	625,000	(1875) 409,100	(1883) 412,300	(1904) 548,900
May..................	769,600	(1876) 769,700	(1880) 647,600	(1904) 533,800
June......	637,900	(1876) 698,200	(1880) 764,000	(1907) 600,300
July...................	303,000	(1876) 539,200	(1883) 646,900	(1905) 410,700

The possibilities of a great rainfall on the surface of the Great Lakes when full to the normal high water level must be considered, and in this connection the diagram below which is transcribed from a technical report of the Miami Ohio Conservancy District and was the result of the most thorough study of the great and prolonged rainfalls within the United States that has ever been made.



ISOPLUVIAL CHART FOR 100 YEAR PERIOD
AND 6 DAY RAINFALL

From Miami Conservancy District
Technical Reports, Part V

This diagram shows that the Great Lakes occupy the most favored spot within the Eastern United States as regards danger of excessive flooding from a great and prolonged rainfall. It will be noted that they lie within the region where the greatest rainfall of a hundred year period during six consecutive days may be expected not to exceed 7 inches.

This diagram made from a most painstaking study of all available records in connection with safeguarding the Miami district against the repetition of disastrous floods of 1913, indicates that these great storms originate, and have their maximum effect in the Gulf of Mexico and decrease northward to but a little more than one-third of the intensity of precipitation at which they start at the Gulf.

If we reckon that the lakes are raised 7 inches by the amount of water falling on their surfaces from such a storm, it is safe to estimate that the additional rise caused by the runoff from their land areas tributary to the lakes will not increase them by more than an additional 3½ inches, or a total of not exceeding 10½ inches, increase in height.

Meanwhile all flood gates will be wide open carrying off the discharge at a rate amounting to about 6.8 inches weighted average depth per week on all the lakes above Niagara, so that the weighted average rise on all these four lakes from such a severe storm would be only about 3.7 inches if it came at a time when all the lakes were at nominal high water.

This analysis indicates that the margin proposed between nominal regulated high water and the limit to which it would be allowable to raise the lake could be less than the 0.99 ft. recommended in this report.

APPENDIX NO. 1

ACCURACY AND PRECISION OF DATA ON ELEVATION AND DISCHARGE OF THE GREAT LAKES

This review of accuracy and precision of data was made early in the course of these investigations because of the obvious importance of being assured of the correctness of the basis for estimates of water yield of the Great Lakes system before reaching conclusions about regulating them and suggesting definite heights and definite limits for their discharge. A statement had been published on high authority that such regulation was a problem so complicated as to be beyond practical solution, and while proceeding to demonstrate that the problem is fully capable of solution it became important to be sure of the data and of every step in the demonstration. Moreover, there was wide-spread doubt about the truth of the statement that the Chicago diversion has lowered Lakes Michigan, Huron, and Erie only about five inches, and it therefore was highly important to make plain the accuracy, once for all, of data for all such estimates.

These notes have been transferred from the main report to this appendix, because, after all, the examination resulted in the acceptance of the accuracy of the previous estimates for the discharge of the Niagara River, upon which the accuracy of mass curves and the precise effects of regulation chiefly depend, precisely as published by various officers and engineers of the U. S. Lake Survey, and mostly summarized in the so-called Warren Report.

While the fact that these data were originally collected under the supervision of specialists, recognized as among the foremost hydrographers in the United States, should have given confidence in their general accuracy, nevertheless they had been collected for purposes different from those now in view, and in which precision of measurement of discharge during winter months was of far less importance than it is in the present problems.

The amounts by which ice-cover and ice-jams had held back discharge have received scant attention until recently, and the accuracy of the estimates of mean annual water yield of the local Lake Erie water shed has been particularly in doubt.

The correctness of the formulas for discharge of certain lakes had been seriously questioned by several of the experts, including Frederic P. Stearns and Gardiner S. Williams, who testified in the suit at law between the United States and the City of Chicago, reported in the Transcript of Testimony before the U. S. Supreme Court, printed in 1924. At that time, after noting the small difference between the average discharge of the St. Clair River and the Niagara River shown by the records, the present writer, among others, concluded that the Niagara gaugings were seriously in error and too small.

He has become convinced by this further examination that **the Niagara gagings were remarkably accurate,** and that while there is some uncertainty in the St. Clair and Detroit River gagings, by far the chief source of uncertainty was the lack of sufficient definite observations from which to determine a proper allowance for obstruction by ice.

Formulas derived from measurements made in summer were commonly used for estimating the discharge from the lakes in winter, and the amount by which the discharge was obstructed by ice seems to have been in many cases simply guessed at.

The estimates that have been made of discharge of the St. Clair and Detroit Rivers disagree seriously at times even in summer, when it is obvious that their actual discharges must have been nearly alike, and this fact shows the uncertainty which attached to measurements of the discharge from Lake Huron.

Whatever errors may exist in the estimates of water yield apparently **have not been caused by inaccuracy in the current meter gaugings themselves,** so much as because of the difficulty of placing these discharge measurements, in accurate relation to the heights in Lakes Huron, St. Clair and Erie, and obtaining a discharge formula, or diagram, by which the rate of discharge on any day in the past 70 years can be found out from the record of the lake elevation on that particular day, as interpreted by a discharge diagram made up from these current meter measurements, which were not begun until about 1898, and which mostly came to an end nearly 20 years ago.

It seemed worth the effort to review these matters carefully with these present purposes in view;

(1) To try to learn the margin of uncertainty.

(2) To put history of the data on record, for convenient reference.

(3) To now set any doubts at rest.

(4) And as an incentive to more precise work upon certain features in future, particularly, a more accurate measurement of discharge during the ice season.

The result of this new examination is that the measurements of discharge in the Niagara River, on which estimates for regulation chiefly depend, are found to have been remarkably accurate and precise, and that the averages of the previous estimates of discharge of the St. Clair and other main rivers, are sufficiently accurate and precise for present purposes.

History of Water Records

All around the Great Lakes, and for many years past, the height of water has been watched with great interest by those concerned with shipping, and from various causes the records of lake elevations have been maintained with excellent completeness and accuracy.

There are scattered early records of lake elevations going back nearly 100 years, some of which are printed in pages 4093 to 4096, of Chief of Engineers' report for 1904; but until about 1855 these gage heights and records appear to have been less carefully looked after, and are much less complete than in later years.

A brief history of the setting of gages for observing lake elevations, during the past 70 years or more, can be found scattered through the annual reports of the Surveys of the Northern and Northwestern Lakes and in the volumes comprising the annual Reports of the Chief of Engineers, U. S. Army.

A convenient summary, prepared by Mr. E. E. Haskell, who for many years had an important part in planning and supervising much of this work, can be found in the Report on the Regulation of Lake Erie, Document 779, 61st Congress, 1st Session, Comprising the Report of the International Waterways Commission, dated January 8, 1910, which, on pages 4 to 7, and in greater detail on pages 63 to 135, gives the history of each gage in condensed form, and the data on gaging from which much of the following record is abstracted.

Beginning in 1860, and continuing for nearly 40 years until the placing of automatic recording gages, observations of the height of each lake and at certain points in the connecting channels were made systematically and recorded once each day, and in some cases three times a day. These records of early height have been averaged to obtain the monthly means given in the published tables, and from which was plotted the diagram of heights following page 198.

Self-registering automatic gages giving a continuous record throughout the day and night were established at nearly all stations at various times from 1899 to 1902.

Lake Superior elevations of water surface were observed at Superior, Wisconsin, near the western end of the lake from 1860 to 1871, inclusive; and at Marquette, Michigan, nearly midway of the lake from 1872 onward. A self registering gage was set at Marquette in 1902. There were a few months without a record and for these elevations were carefully interpolated by comparison with other gages.

At Sault St. Marie, about 7 miles down from the Eastern end of Lake Superior where slightly lowered by the starting of the current, water elevations were observed at the pier above the locks, on a staff gage from November 1870 to 1899, and since that time by means of a continuously recording automatic gage.

Lake Michigan's elevation has been observed at Milwaukee, about midway of the westerly shore, continuously since 1860.

Lake Huron's elevation was continuously observed at Harbor Beach (formerly called Sand Beach), about 59 miles upstream from its outlet into the St. Clair River, beginning with a staff gage in 1874, and by self recording gage since that time. Lake Huron's elevations for the 15 years prior to 1874, at Harbor Beach, were derived from observations at other points (see Report, Chief of Engineers, 1904, page 4105).

In the Saint Clair River at a point about 0.8 mile below the end of Lake Huron, at the Grand Trunk Railway pier, elevations have been observed continuously since 1899. For the preceding 39 years elevations for this location are derived from the Harbor Beach gage by a series of carefully adjusted comparisons, which compensate by a constant quantity of 0.7 ft. for the slope between, although obviously this must vary slightly with the quantity of water flowing, and with the force of the wind.

At the St. Clair Flats Canal, near the head of Lake St. Clair, the authentic records began in July 1872 and are continuous with a few exceptions. Missing values for this series are from comparisons with record at the Light House depot, Detroit, and at the Detroit Water Works aided also by observations at Amherstburg at the western end of Lake Erie. By similar comparisons the St. Clair Flats Canal record was extended back to 1860. Near the lower end of Lake St. Clair, at Windmill Point, water elevations have been observed since 1897, with few exceptions. Omissions have been filled in and extended back by comparison with nearest gages.

The records of this gage at the head of the St. Clair Flats Canal are of doubtful precision for a time within which probably there was a settlement of the gage support amounting to a few inches (see Warren Report, page 357–8).

Lake Erie's daily elevation of water surface has been observed continuously since 1860, at Cleveland, with a few brief exceptions which have been supplied by interpolation from observations at Erie, Pa.

At Amherstburg, Ontario, on Lake Erie near the outlet of the Detroit River, observations began in 1899. Figures for earlier months have been supplied by comparison from the Cleveland gage records.

At Buffalo, Lake Erie's daily height has been observed many years, but the records prior to 1887 were accidentally destroyed. Missing values back to 1860 were supplied from the Cleveland records.

On Lake Ontario, elevations were taken continuously at Charlotte N. Y. since 1860, also at Oswego, N. Y. since 1860. It is noted that on the relatively rare occasions when the Oswego River is in high flood, this may affect readings of this gage.

Below where Lake Ontario slowly narrows into the St. Lawrence River, at Ogdensburg, N. Y., gage heights have been observed intermittently. The monthly averages for this location have been largely derived from the observations at Oswego.

There are many discontinuous records of elevations for each of the lakes long prior to 1860, to be found scattered through various publications, which are of interest as showing successive cycles of high and low lake levels, similar to those of more recent years; but it has not seemed worth while for present purposes to try to use estimates of discharge based upon these less definite records of more than 65 years ago, in the mass-curves, or in other computations for finding the effect of regulation upon increased depth. The 65 years of continuous records since 1860 appear ample for all present purposes of testing out by computation, the proposed methods of regulation.

All of the records of elevation described above have been compensated for and adjusted to conform to the datums of the precise levels of 1903, before using them in the present report, and are given in feet above mean tide in New York Harbor.

This has not taken account of the slow tilting of the earth surface, upward toward the northeast which for 75 years or more past has been going on in various localities about the Great Lakes at about the rate of somewhere between one foot and a half foot per 100 miles per century, as shown by the investigation reported on pages 149 to 171.

Discharge Measurements

Accurate direct measurements of discharge of the Great Lakes have been few and far between.

The precise quantity discharged was of little interest to the general public or to others than engineer specialists, until long after the Chicago Diversion. It became of special interest only subsequent to the development of water power on a large scale on the Niagara and St. Lawrence Rivers, and as a result the recent awakening to the importance of conserving these water resources to the utmost. The height of the lake surface and the depth available for shipping over the shoal places were, until recently, the chief features on which public interest was focussed.

To make a precise measurement of the discharge of any one of these great rivers, the St. Marys, the St. Clair, the Niagara or the St. Lawrence, is an exceedingly difficult and costly matter and it seems not to have been attempted by the Government engineers in charge of the Lake Survey until many years later than the time when accurate and systematic records of height had become a matter of daily routine.

After a few measurements of the discharge from Lakes Huron and Erie, in 1869, no further measurements of discharge from Huron or Erie were made for about 30 years, or until the investigations by the Board on Deep Waterways, about 1898.

No thorough investigation or analysis of the natural causes which lead to variations in level and discharge, such as rainfall and evaporation, appears to have ever been published among the papers of the Lake Survey, and although evaporation is a great factor, there has never been reported any serious attempt by the survey to measure or record this, and so far as known there is not one proper floating or other evaporation tank with accessories maintained anywhere about the shores of the Great Lakes.

The attention of the engineers in charge appears to have been focussed chiefly on making excellent charts, constructing efficient aids to navigation and to keeping records of the varying levels of the lakes. When they finally undertook gagings of river discharge, these, for the time being, and during the navigation season, were carried out with most adimrable exactness.

In planning deep waterways from the Great Lakes to the sea, problems of regulation arose, which required making elaborate measurements for establishing formulas and diagrams for giving the rate of discharge for any height of lake: by means of which the records of height for 40 years past, and during many years to come, could be translated into terms of discharge.

The few earlier gagings of river discharge are worthy of notice. In 1868 and 1869, Mr. D. Farrand Henry of Detroit, an assistant engineer in the U. S. Lake Survey, made measurements of the discharge of the St. Clair River, also of the Niagara River, which are described in the Report of Chief of Engineers for 1870, pages 554 to 592 and pages 616 to 631, and also described in the Journal of the Franklin Institute of Philadelphia, in a paper by Mr. Henry, published serially in 1871 and 1872.

These early measurements by Mr. Henry are of particular interest as marking the beginning of the appreciation of the superior accuracy of the current meter of the revolving wheel or screw type, to that of the double float, which had been used by the U. S. Engineers in the gagings of discharge of the Mississippi River, and described in the treatise of Humphreys and Abbott, and prior to that time accepted as their standard method.

From reading the description of the methods of these early measurements and from observing the lack of appreciation developed up to that time, of the many precautions subsequently found necessary to ensure precision in the measurement of total discharge in these rivers of rapidly changing slope, and particularly after reading General H. L. Abbott's expressions of strong dislike for the new methods that were being tried out (pages 616–631 Ch. Engrs. Rept. of 1870), it is plain that while these early gagings of river discharge must be accepted as preliminary approximations, it appears probable that up to the date of Mr. D. Farrand Henry's work, no great river had ever been gaged with the degree of precision which he attained in his averaged results on the St. Clair River.

Assistant Engineer Henry's pioneer work with the rotary current meter pointed the way toward the success and to the remarkable precision of measurement of thirty years later. Time has vindicated many of Mr. Henry's conclusions and the method of measurement by double floats, which he supplanted, has, since his time, fallen into total disuse.

The next discharge measurements on the Niagara River appear to have been made in 1899 for the Board of Engineers for Deep Waterways, and are described at length by Mr. E. E. Haskell, Assistant Engineer in charge, in Appendix No. 7 of their report.

In Document 779, 61st Congress, 1910, on the Regulation of Lake Erie, Mr. Haskell presents an excellent history of the gagings of discharge of the Great Lakes, more particularly of the Niagara River, and describes the discharge formulas derived for the outlet from each lake.

To make even a single complete and accurate gaging of one of these great rivers requires much preparation. To establish a rating diagram requires scores of measurements and the work of a large engineering party for an entire summer, but once made, it is good for translating records of elevation into rates of discharge until a change occurs in the channel depth, or in its area, or until obstructions occur in the channel as a result of deposits, or of change in structures, or from growths of water weeds, like eel grass, or from obstruction by use.

Accuracy in data for discharge is of such importance in studies for regulation, and for water power development, that a brief review of the discharge measurements on the Great Lakes is presented, beginning near the source and proceeding downstream.

Formulas for Lake Superior Discharge

At Lake Superior the earliest precise gagings upon which a satisfactory discharge formula or rating curve could be based, appears to have been made about 1896. The determination of 1896 was used for the 32 years, January 1860 to September 1901.

After that time so many changes were made affecting the discharge, while building new locks, new water power plants and improving conditions for navigation by dredging, that from time to time, in order to cover a period of 48 years, about a dozen discharge formulas were devised for the St. Marys River, each to meet one temporary condition, but the differences in discharge given by the different formulas for any one elevation have not been large.

New current meter gagings were made in 1901 and 1902, at the International Bridge cross section.

A fairly complete résumé of these changes and of the various formulas for discharge from Lake Superior is presented by Mr. Haskell in pages 22 to 32 of the Report on the Regulation of Lake Erie, in 1910.

After the partial completion of the regulating gates across the outlet of Lake Superior, it is obvious that the rate of discharge could no longer be measured solely by the recorded elevation of Lake Superior. The first set of these regulating gates was installed in 1901–02. This left an opening which was partially closed by additional gates in 1911 and 1916, and the closure completed in 1920.

Since Lake Superior is already provided with regulation works and its gagings are of only secondary interest in the present discussion, there is no doubt about their accuracy being sufficient for all present purposes. The following notes will indicate that the estimation of its discharge as presented in the diagram of average monthly discharge for all of the lakes, presented on page 235, rests on carefully considered data.

Discharge measurements were made at Sault Ste. Marie in 1896, 1899, 1900, 1901, 1905 and 1908. The following formulas, as given in the Chief of Army Engineer's Report for 1903, page 2857, were derived from the gagings of 1896–99.

During the building of the International Bridge piers, from 1887 to 1892, the area of the channel was somewhat reduced, necessitating different formulas for different periods.

Before 1888,

Discharge in c.f.s. = 46,047 + 19,429 (Elev. of Lake Superior—600).

From 1888 to 1895, inclusive,

Discharge in c.f.s. = 39,798 + 17,656 (Elev. of Lake Superior—600).

From 1896 to 1898, inclusive,

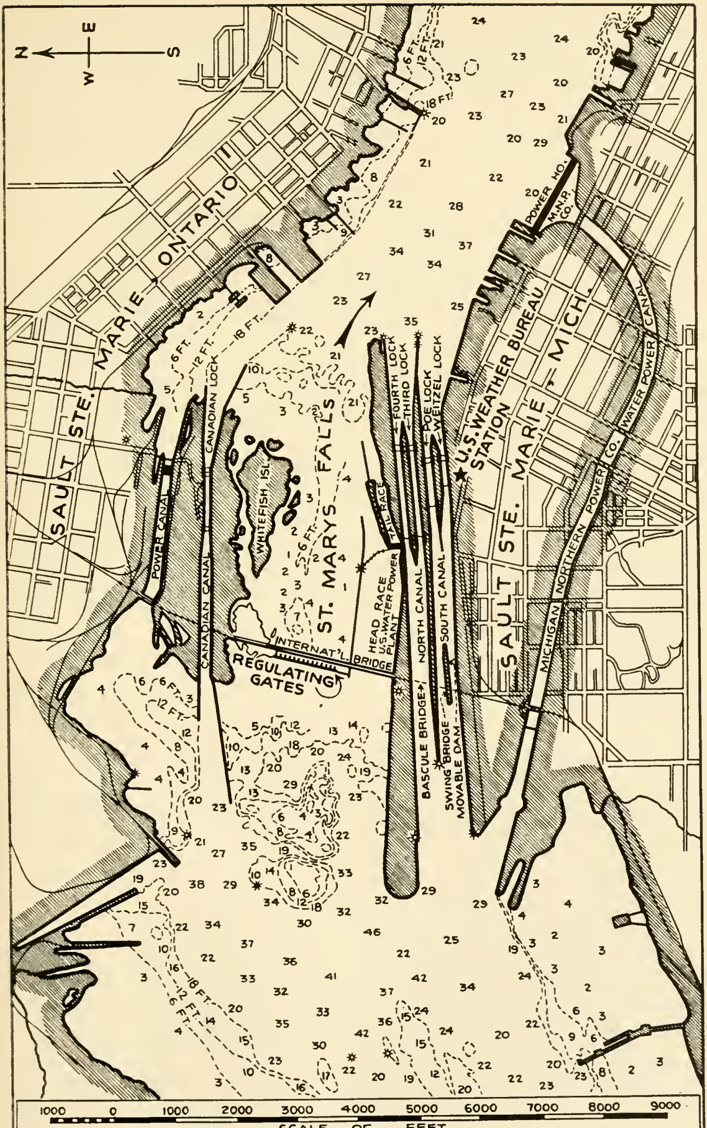
Discharge in c.f.s. = 43,466 + 17,656 (Elev. of Lake Superior—600).

After 1898,

Discharge in c.f.s. = 49,235 + 17,656 (Elev. Lake Superior—600).

Since 1908, the restrictions in the St. Marys River have been increased due to the construction of locks and regulating sluices which makes new formulas for discharge necessary.

Since 1902, the estimates of discharge shown on the diagram were plotted as received from Mr. L. C. Sabin, April, 1925. These are understood to include the discharge through the power canals and locks.



CHANNELS, LOCKS AND REGULATING GATES AT SAULT STE. MARIE.

Formulas for Discharge from Lake Huron

Discharge measurements have been made during the years 1867—69 1899, 1900, 1901, 1902, 1908, 1909, and 1910.

The latest equation as given in the Chief of Army Engineers Report for 1912, page 3547, is,

Discharge in c.f.s. $= 3758$ [(Ft. Gratiot—567.51) $+1.125$ (St. Clair Flats—567.51)] (Ft. Gratiot—St. Clair Flats)$^{1/2}$.

This has been modified as given in Warren Report, page 355, so to use elevations of Lake Huron at Harbor Beach instead of at Ft. Gratiot, as follows:

Discharge in c. f. s.
$= 3820$[(H. B.—567.50) $+1.135$ (S. C.—567.50)] (H. B.—S. C.)$^{1/2}$.

The flow during the open season, since 1902, as given on the diagram on page 235, has been computed by the above formula.

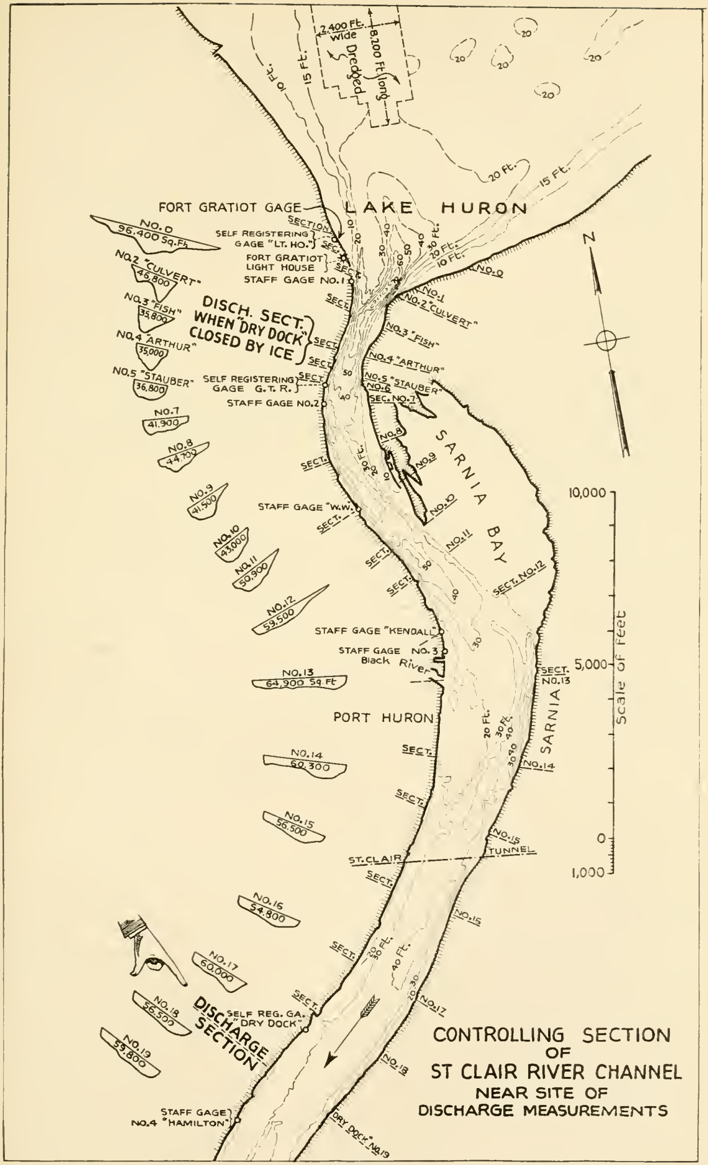
Prior to 1903, the discharge as shown on the diagram, was obtained during the summer, June to November inclusive, by means of the formula, as given on page 2821 of the Report of Chief of Engineers for 1902, as follows:

Discharge in c.f.s.
$=190{,}700+37{,}500$ (Harbor Beach—580) —18,000 (St. Clair Flats—575).

For the winter months, December to May inclusive, the discharge was computed by the equation given on page 5362 of the Report of Chief of Engineers for 1900, and uses the Elevation of Lake Huron at Harbor Beach only:

Discharge in c.f.s $=194{,}900+19{,}060$ (H. B.—580).

The values thus obtained were corrected for retardation effect of ice as per schedule given on page 2858 of the Chief of Engineer's Report for 1903, and quoted in the first column of figures in the following table. The more recent estimates are given in parallel column for comparison.



CONTROLLING SECTION OF ST CLAIR RIVER CHANNEL NEAR SITE OF DISCHARGE MEASUREMENTS

Estimated Average Retardation by Ice in St. Clair River

	Per Chief Engineers Report, 1903	Per Mr. Richmond In Warren Report
December	8,600 c.f.s.	6,200 c.f.s.
January	41,750 c.f.s.	27,500 c.f.s.
February	60,833 c.f.s.	42,500 c.f.s.
March	55,700 c.f.s.	28,000 c.f.s.
April	39,550 c.f.s.	14,300 c.f.s.
May	11,000 c.f.s.	1,500 c.f.s.
Total	217,433 c.f.s.	120,000 c.f.s.
Or for the year	18,120 c.f.s.	10,000 c.f.s.

Unfortunately these figures are far from precise either in their original measurement or in their application. They are both extremely crude approximations. In some winters there is very little obstruction and in others much obstruction. The practical importance of this matter seems not to have been recognized as future data for estimates of the possibilities of lake regulation or conservation by storage for power development.

Comparisons of Discharge of St. Clair and Detroit Rivers

The Detroit River discharge is naturally larger than that of the St. Clair River because of the additional yield from the drainage directly tributary to Lake St. Clair. Formulas for the Detroit River discharge were derived by gagings at Fort Wayne, Michigan, by the United States Lake Survey in the summers of 1901 and 1902, using as the controlling data, the elevations of Lake St. Clair by the Windmill Point gage, and of Lake Erie by the Amherstburg gage at the head of the lake.

A comparison of estimates of discharge, made from simultaneous observations of elevations of Lakes Huron and St. Clair, and by the application of the formulas for the St. Clair and Detroit Rivers show wide differences, but are useful in showing the errors in estimating discharge liable to be caused by the presence of ice.

The lower diagrams on page 491 show such a comparison.

Since the discharge through the St. Clair River during the winter months when there is ice cover or ice-jams is very irregular and its estimate very uncertain, it had been hoped to obtain more accurate estimates of discharge at such times by the use of formula and gage heights for the Detroit River. The St. Clair River, however, has finally been accepted as the better place for measurement.

Measurements were made during the winters of 1900, 1901 and 1902, from which the above tables of estimates for the retarding effect of ice have been derived. Application of these values in all other years, gives results that are often in error.

Formulas for Discharge from Lake Erie

Discharge measurements have been made during 1898, 1899, 1900, 1907, 1908 and 1913, and from the results various formulas have been derived for computing values of discharge from elevations of Lake Erie.

The discharge diagram for Lake Erie, page 235, prior to 1903, was plotted from values obtained by using the formula:

Discharge in c.f.s.

$$= 158{,}500 + 22{,}462 \text{ (Elev. at Cleveland—570)};^{*}$$

as given in Report of Chief of Engineers for 1903, page 2858: where it is stated that the formula requires two small corrections:

First, an addition for diversions through the Erie and Welland Canals, estimated at that time to be 1,200 c.f.s. and 1,100 c.f.s. respectively.

Second, "A correction due to difference between the zeros of the gages at Cleveland and Buffalo" (see page 4070, Report of 1904), which was estimated to be 8,500 c.f.s. for calm weather. But it is further stated in the report, page 2859, that "On account of the remaining uncertainties in these two corrections, neither of them has been applied."

Subsequent to 1903, the discharge diagram is plotted from the tables of estimates received from the U. S. Lake Survey office in December, 1924 and March, 1925, and which were computed from the equation:

$$\text{Discharge in c.f.s.} = 3{,}904 \text{ (Buffalo Gage—558.37)}^{\frac{3}{2}}$$

It is understood that no corrections were made in the elaborate tables of discharge, printed in the report of the International Board on the Regulation of Lake Erie in 1910, for the retarding effect of ice in Niagara River, nor for the diversions through the Erie, Welland Canals and Chicago Drainage Canal, such corrections have been applied in the estimates of the present report.

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*Progressive earth-tilt obviously has changed the relation of the Cleveland gage so that the estimates for earlier years than 1903, based on the Cleveland gage, should be corrected. The diagram on page 162 indicates that for example, 33 years earlier, or in 1870, the outlet of the lake was 0.29 foot lower than in 1903 relatively to the Cleveland gage. Wherefore, the discharge in 1870 was about 6170 cu. ft. per sec. greater than given by this Cleveland formula.

Formulas for Discharge from Lake Ontario Through St. Lawrence River

Discharge measurements have been made during 1900, 1901, 1908, 1911, 1913, and 1914.

Prior to 1903 the curve shown on the diagram on page 235 was plotted from values obtained by formula:

Discharge in c.f.s. = 94 683 + 25,761 (Oswego Gage—240)

A correction during winter months for retarding effect of ice in the St. Lawrence River had been made as follows:

January	6.2%
February	9.0%
March	5.3%
April	1.2%

During 1903 the Gut Dam was completed and a new formula for discharge was needed. From the gagings of 1908 and 1911 the following formula was derived (see Chief of Engineers Report for 1912, page 3547).

Discharge in c.f.s = 4,009 $(\text{Oswego}—230.65)^{\frac{3}{2}}$

Later gagings, in the years 1913 and 1914, caused a change in the formula of 1912, so that, since 1903, the values of discharge as estimated at the U. S. L. S. office and p'otted on the diagram on page 235, for summer months, May to November inclusive, were computed from the following formula (see Chief of Engineers Report for 1917, page 1928).

Discharge in c.f.s = 3,428 $(\text{Oswego Gage}—229.13)^{\frac{3}{2}}$
except for the year 1903, which was computed from Lock 23.

Discharges, December to April inclusive, as given in tables received from the U. S. L. S. office, were computed, since 1903, from gages at Oswego, Lock 27, Lock 24 and Lock 23 and the smallest valve accepted.

Discharge in c.f.s. = 3,896 $(\text{Lock } 27+5.86)^{\frac{3}{2}}$

Discharge in c.f.s. = 2,755 $(\text{Lock } 24+10.70)^{\frac{3}{2}}$

Discharge in c.f.s. = 2,589 $(\text{Lock } 23+12.03)^{\frac{3}{2}}$

Mr. Richmond, in the Warren Report, page 364, estimates the retarding effect of ice in the St. Lawrence River as follows:

December	3,600 c.f.s.
January	9,900 c.f.s.
February	19,100 c.f.s.
March	13,800 c.f.s.
April	6,400 c.f.s.
Total	52,800 c.f.s.

or an average of 4,400 c.f.s. per year.

Gagings of Lake Michigan-Huron Discharge

The principal series of measurements of discharge from Lake Huron were made in the head of the St. Clair River, about 5 miles below the end of the lake, at the so-called "Discharge Section," which is near the lower end of a fairly straight reach about 2 miles in length, at various times from 1899 to 1902, mostly under the supervision of Mr. Louis C. Sabin, C. E., who until recently has been the engineer in charge of the navigation locks and their appurtenances on the United States side of the International Boundary at Sault St. Marie.

The Deep Waterways Report of 1900, although giving a full account of the elaborate Niagara River discharge measurements, which that Board inaugurated, says little about the discharge from Lake Huron.

The Board ran new lines of precise levels up along the Detroit and St. Clair Rivers, and determined the profile and slope of these rivers with much care and its report presents diagrams of the slope between Lake Huron and Lake Erie, useful while considering the large increase of elevation of Lake Erie proposed by the Deep Waterways Board, and particularly useful in demonstrating that by raising the level of Lake Erie as proposed, the back water caused by these proposed gates in the Niagara River would extend back through the Detroit and Saint Clair Rivers, slightly deepening their channels, and would slightly raise Lakes Huron and Michigan, and would slightly increase the depths in the St. Marys River up to the locks at the Sault.

The 1910 Report on the Regulation of Lake Erie by the International Waterways Commission also says little about precise measurements of the discharge from Lake Huron, and gave no consideration to the great help to navigation or power that could be had from regulating the discharge and levels of Lakes Michigan and Huron, although their outlet rivers are international waters. It seems to have confined its studies to holding Lake Erie at a high and nearly constant elevation, and to the effect of this on an unregulated Lake Ontario.

This 1910 Report published values for the Lake Huron discharge admittedly in error; for its says (page 33, paragraph 65):

> "Ice gorges occur in the St. Clair and Detroit rivers nearly every winter, creating an abnormal slope in the river that is gorged. Under such conditions the discharge value computed from the river not gorged has been used as the correct monthly mean inflow to Lake Erie—"

In other words **the summer equation** determined in 1899–02, **was applied to winter conditions,** with the result that the results published in this elaborate report of 1910, for the discharge of the St. Clair River probably averaged for the year at least 10,000 cu. ft. per second more than the actual discharge, or were 6% too large in the annual average because of ice obstruction alone, and for several months in extremely severe winters the discharge as published may have been double the actual discharge, judging by what was found by the winter measurements by Engineer Sabin, in 1901.

A proper allowance for the effect of ice, in causing much smaller discharge than is indicated by formulas derived from gagings made in summer, is of the utmost importance, and for making this allowance, unfortunately, very little information has been recorded about the obstruction by ice from day to day.

That temperature records alone, are an uncertain guide as to the changing retardation from ice-cover, or to the sudden changes in discharge caused by the forming of an ice-jam, or its breaking away, is plainly shown by placing a log of these discharge measurements in the ice season of 1901 alongside the record of temperatures, page 36.

This absence of ice records is another illustration of the fact that relatively little importance seems to have been given in the past to accuracy of winter discharge, probably because it was a matter that did not directly concern navigation.

Another cause of uncertainty about estimating the discharge from the records of lake elevation for the early years, or prior to the extensive discharge measurements of 1899–02, is found in the reputed change in the relation of discharge to elevation of Lake Huron, which was discussed at length in the Deep Waterways Report of 1900, with the conclusion, at that time, that the dredging of lake outlet or scour in channels within the previous 10 or 20 years had caused a lowering of Lake Huron relative to Lake Erie, amounting to about one foot.

Note—Later investigations have shown this apparent lowering was in part due to earth-tilt and in part to a lessened discharge leaving only about 4 inches of the observed lowering due probably to dredging and scour.

This question of change in the discharge from Lake Huron corresponding to a given elevation is discussed in Appendix No. 3 of the present report.

Meanwhile, it may be of interest to turn to the cut on page 513 showing the remarkable extent of these changes about 1890 and about 1910. Apparently it was doubtful about this uncertainty in the discharge of Huron measured by the St. Clair River formula that chiefly led Mr. Haskell to use the Detroit River gage heights for his estimates of discharge from Lake Huron in his 1910 report.

Very full information about these St. Clair River gagings is given in the Report of the U. S. Chief of Engineers for 1900, page 5362.

The discharge from Lake Huron was derived in terms of the elevation shown by local gages in the St. Clair River, but formulas were worked out by which the elevation of Lake Huron 59 miles away, at Harbor Beach could be used.

In the effort to obtain precise and concurrent results it was found after a time, that the elevation of Lake Erie exerted a disturbing influence, and must also be taken into account; and that the gage in the St. Clair Flats Canal, close to Lake St. Clair, was subject to less disturbance of elevation than the gages in Lakes Huron and Lake Erie. The formula finally used in computing the whole series of discharges from 1860 onward was given in terms of the elevation by two gages, the Harbor Beach gage and the St. Clair Flats Canal gage.

This formula is expressed in the Discharge Diagram printed on page 32.

Particularly elaborate arrangements were made for keeping constant record of the fluctuating water levels of lake and river while the current meter gagings were in progress by means of four self-recording water stage gages, one located in Lake Huron near the Fort Gratiot Lighthouse, another about a mile down river, known as the Grand Trunk Railway gage, a third near the "Discharge Section" known as the "Dry Dock gage" and the fourth near the lower end of the St. Clair River, known as the "St. Clair Flats Canal gage." Careful observation also was maintained of the total fall and slope between Lake Huron and Lake Erie.

An innovation in methods of current-meter velocity measurements was developed, in the simultaneous use of a string of current meters, all located in the same vertical plane, for the simultaneous determination of velocity at about nine different points. By this means the time for making a complete gauging all of the way across the river was greatly lessened, thus permitting the whole to be made under more nearly constant conditions.

Mr. Sabin's description of methods and results is very complete. In brief, many precautions were taken to insure accuracy, and it appears certain that nothing better in precise river gaging under such difficult conditions has ever been accomplished anywhere. The difficulties here come chiefly from having to deal simultaneously with elevations in the two lakes, Huron and Erie, under conditions resembling those within a channel 80 miles long, containing a series of deeply submerged weirs, each with an extremely broad irregular crest, subject to sudden changes in depth both above and below.

A continuation of these gagings of the outflow from Lake Huron, and further development of formulas for obtaining the discharge from records of lake elevations, is described in the Chief of Engineers Report for 1902, page 2819; and measurements of discharge of the Detroit River are described on page 2871, Chief of Engineers Report of 1903.

No Change of Regimen in 30 Years

It is of particular interest to note Mr. Sabin's comparison of these extremely elaborate and precise St. Clair River gagings of 1899–1900, with the less precise gagings by the method of double-floats in 1867 and by both floats and early forms of current meters in 1870 (see Ch. Eng'rs Report, 1900 page 5,385), because this concurrence, of itself, would warrant carrying back the application of the discharge formulas and diagrams made in 1900–02 to the lake elevations recorded during the preceding 45 years.

This concurrence in discharge measurement **also tends to confirm the correctness of adjustment of differences between the two gages to compensate for earth-tilt,** after which the difference to be attributed to enlargement of channel by dredging and scour is only about 0.4 ft., which should make the gagings of 1900 give about 7600 c.f.s. or 4% more water for the same gage reading than was given by the D. Farrand Henry gagings of 30 years before.

The differences in discharge for the same lake elevation by three gagings in the years 1867, 1868 and 1870 averaged the same as those of the years 1899–02, within less than 1 per cent., one gaging being about 2½ per cent higher and two being about 2½ per cent lower.

The average annual results of these two sets of gagings 30 years apart are compared in detail on page 503.

Accuracy of Discharge Estimates

The diagram on page 32 is made from the formula finally worked out at the U. S. Lake Survey office from the discharge measurements made during the years 1899–1902, 1908–1909 and 1910, and gives the discharge in terms of the heights in both Lake Huron and Lake St. Clair.

Variation in height of Lake St. Clair has less effect upon the discharge than an equal amount of change in height of Lake Huron. In other words, within these limits a change of 0.25 foot in the upstream head on this deeply submerged weir changes the discharge as much as a 1.0 ft. change in the downstream head.

A second diagram is presented, on page 33, for discharge of Huron in terms of Elevation of Lakes Huron and Erie. This was prepared under the supervision of the present writer, by combining the formula for discharge of the St. Clair River in terms of elevations of Lake Huron at Harbor Beach and Lake St. Clair at the Flats Canal with the formula for computing the heights of Lake St. Clair from the elevations of Lake Huron and Lake Erie. The use of the elevation of Lake Erie instead of elevation of Lake St. Clair, as the second factor in controlling the discharge appears more logical, since the St. Clair elevation depends on that of both Huron and Erie.

It is of interest to note the relative small effect of a change in Lake Erie's elevation on the discharge from Lake Huron. It has only about 0.17 the effect of an equal change in Lake Huron's elevation.

Natural causes, such as strong winds, barometric waves or seiches, ice gorges and local rains, perhaps also local changes in evaporation, are continually throwing out of equilibrum, the relations of elevations of the different lakes, Huron, Erie and St. Clair; therefore the fall from lake to lake varies largely from day to day, and this in turn affects the rate of discharge. This is illustrated by the diagram on page 513 showing the great differences in fall between Huron and Erie in two successive years, and a comparison with long term means.

Because of these changes, the degree of accuracy that can be obtained in establishing a relation between the discharge and the height, in either one of the Great Lakes, is much less satisfactory than the accuracy of the discharge measurement itself. This is particularly true in the case of Lake Huron. In other words, because of disturbance by wind or ice, change in river bed, or change in level of the westerly end of Lake Erie by wind or seiche, the actual discharge may not always be the same on two different days upon which the recorded elevation of Lake Huron is the same at Harbor Beach, 59 miles north.

After a study of the complications and difficulties of establishing a correct discharge diagram for the St. Clair River either in terms of elevation of Lake Huron only, or in terms of both Huron and St. Clair, the present writer has come to believe that both for the period from 1855 to 1890 and for the later years, **the conditions for accurately estimating the discharge from Lake Huron through either the St. Clair or the Detroit River from the recorded elevation of the adjacent lakes, are much less satisfactory than those for the accurate estimation of the discharge from Lake Erie,** made in the head of the Niagara River, where the lake elevation is measured by a nearby gage and where there is a permanent river-sill formed in the broad, level limestone ledge, also a larger, steeper fall within 3 miles below outlet of lake, also less interference from ice, and no such complication with two other fluctuating lakes, as is presented in Lakes St. Clair and Erie while trying to derive a discharge diagram in terms of the Elevation of Lake Huron.

The discrepancies and uncertainties found in comparing discharges given by discharge formulas, year by year, for outlets of Huron, St. Clair and Erie may all be charged against these vagaries of the St. Clair and Detroit Rivers; and the **Niagara discharge as determined from the observed elevation of Lake Erie at Buffalo may be taken as the standard, with great confidence in its accuracy.**

This Buffalo gage is so near to the location of the cross-sections that control the discharge from Lake Erie that no substantial error is introduced into this estimate of discharge by earth-tilt.

Questionable Yield of Lake Erie

The small net water yield of Lake Erie and its local water shed long seemed out of line with that of the other Great Lakes, and this among other reasons had long ago led to questioning the accuracy of the discharge measurements by which this had been determined. This small excess in the discharge of the Niagara River over that of the St. Clair and Detroit Rivers indicated error in measurement of discharge at either the outlet of Huron or the outlet of Erie.

Note—The allowances recently made for the retarding effect of ice in the St. Clair River with the result of a smaller estimate for the Lake Huron discharge now brings up the Lake Erie local yield to a more reasonable figure.

Mr. Russell, in U. S. Chief of Engineers Report for 1904, page 4,125, contributed an important study of run-off and evaporation, and regarding his comparison of the estimates of yield measured in the outlets of Huron and Erie, said:

"The average discharge of Detroit River for 11 years 1893 to 1903, is on the average	193,854 c.f.s.
The discharge of Niagara River for the same time is	197,328 c.f.s.
The excess thus shown gives the yield of the local Lake Erie drainage area is only	**3,474 c.f.s.**
which seems much too small.	
According to Mr. Russell's estimates of run-off from local drainage less evaporation, the yield of Lake Erie's local drainage, should be	30,100 c.f.s.

Mr. Russell concludes, "It would require a very great and totally inadmissable evaporation from the lake to have the difference in discharges as small as the observations indicate."

Mr. Frederic P. Stearns deduced the average net yield of the local Lake Erie drainage area (including Lake St. Clair), from probabilities of run-off and evaporation for the 11 years, 1883 to 1903, inclusive, for June to November inclusive as about .... **24,000 c.f.s.**

(See Transcript of Testimony, Vol. VII, page 574.)

which is .... 6,100 c.f.s.

less than Mr. Russell deduced for the whole year, as given above.

By the figures adopted recently by the present writer.

Average discharge from Lake Erie for 65 years corrected for ice (see page 38)	207,900 c.f.s.
25-year average yield of Lake Erie plus yield of St. Clair, 1900–1924, (see page 51)	25,800 c.f.s.

Probable average yield of Lake Erie plus St. Clair for 65 years*	**26,500** c.f.s.
Probable average discharge of St. Clair River for 65 years corrected for ice (see page 38)	181,400 c.f.s.
Probable yield of local drainage area of Lake St. Clair, by estimation from its drainage area	4,300 c.f.s.
Apparent net yield of Lake Erie exclusive of Lake St. Clair by difference after correction for ice	22,200 c.f.s.

The yield for the 34,680 sq. miles immediately appurtenant to Lake Erie, of which 28.6 per cent is water surface, found by subtracting from the discharge of Lake Erie that of Lake Huron for a given period, and after making due allowance for change in elevation of lakes, has at times been surprisingly small. There are, at times, several months in succession in late summer when a negative yield is probably caused by evaporation from this vast area in excess of local inflow, outside the St. Clair River. But for any term of several years in succession it would seem by analogy from other experience that the combined yield of Lake Erie and Lake St. Clair should average even more than the 26,500 c.f.s. shown by the revised computations above unless this lake is subjected to abnormally large evaporation loss.

Plainly, evaporation is an extremely large and variable factor, but there are no good data for a precise estimate of the evaporation over this broad surface, nor are there good data for giving the percentage of run-off to rainfall from the local land area, nor do we know if precipitation over the broad lake surface averages precisely the same as over adjacent land.

Nevertheless, estimates like the following serve to give a more definite conception of the net effect of varying amounts of evaporation and rainfall, and as a basis for judgment about the correctness of the several estimates of respectively, 3,740 c.f.s., 30,100 c.f.s., 24,000† c.f.s. or 22,200 c.f.s. quoted above, for yield of Lake Erie, exclusive of Lake St. Clair.

Since there are no satisfactory measurements of yield of the Lake St. Clair drainage, separate from that of Erie, both yields will be figured together.

*During the 29 years, 1871 to 1899, the rainfall, as deduced from records at several stations around Lakes Erie and St. Clair is shown to have been about 3 per cent greater than during the past 25 years, 1900 to 1924. Assuming the same percentage of run-off from the land drainage, this would indicate 1.5 per cent larger net yield or an average of 27,100 c.f.s. for the 29 years, thus giving an average net yield for 54 years, 1871 to 1924, of 26,500 c.f.s. From the few rainfall records that are available for the 11 years prior to 1871 and from the computed discharges from the several lakes, there seems to be no reason for expecting this average for the 54-year period, 1871 to 1924, to be much different than the probable average for the 65-year period, 1860 to 1924, of 26,500 c.f.s.

†This value of 24,000 c.f.s. as deduced by Mr. Stearns represents the yield of both the Lake Erie and St. Clair drainage areas for the open season months only, June 1 to November 30 inclusive.

Estimates of Yield of Lake Erie from Outside Observations of Rainfall and Evaporation

Assume an annual total depth of rainfall, including melted snow, of	35.0 inches
Over both water and land drainage of Lakes Erie and St. Clair	41,100 sq. mi.
This, if none was lost, would yield a constant discharge of	105,900 c.f.s.
Of which the gross yield from the 30,700 sq. mi. of land would be	79,100 c.f.s.
Of which the gross yield from the 10,400 sq. mi. of water would be	26,800 c.f.s.
If, say, at least 35 per cent of the rain falling on land in this flat and much cultivated region, is delivered into the lake this would amount to an annual yield averaging 12.25 inches in depth of run-off, or	27,700 c.f.s.
Making a total expected delivery into lake from land and water exclusive of yield from Lake Huron	54,500 c.f.s.
An average evaporation from water surface of lake averaging 36 inches per year would take away	27,700 c.f.s.
And would leave from the 54,500 c.f.s as the net run-off from land and water of the local drainage area of Lake Erie and Lake St. Clair	26,800 c.f.s.
Which altho small seems a not unreasonable quantity to expect and is only 1.0 per cent larger than the above estimated average for the past 65 years	26,500 c.f.s.
It is derived from the long term records, after correction for ice which seems an excellent confirmation. In the writer's judgment, based largely upon data described in Appendix No. 2, evaporation from Lake Erie probably averages about	36.0 inches

REDUCTION OF DISCHARGE BY ICE

The figures deduced by Mr. Richmond in the Warren Report, given on page 37 of the present report, and tentatively adopted by the present writer for lack of something better, appear to demand further comment.

Within the past few years the practical importance of precise knowledge regarding the amount by which the discharge of the several lakes has been lessened by ice covering, or by ice gorges, in the St. Marys, St. Clair, Detroit, Niagara Rivers and in the head of the St. Lawrence River, has become very greatly increased because of water power development on the Niagara and St. Lawrence Rivers, and by the evidence of a rapidly increasing demand for electric power, which may, within the next half century, call for conserving to the utmost the great natural resources found in the water yield of the Great Lakes.

The only definite measurements of the effect of ice in obstructing the discharge are those made in the St. Clair River in the winter of 1900–1 by Mr. L. C. Sabin. The only attempts to apply the results of observation in corrections for ice effect found in the published reports of the U. S. Army engineers connected with the Great Lakes service are of a general character, applicable year after year as a constant, invariable deduction without change for differences in seasonal temperatures from year to year. The measurements, guesses, notes and conclusions by Mr. Sabin, Mr. Russell and Mr. Richmond are summarized below:

St. Marys River-Ice Effect

Mr. Richmond reports that the retardation of flow in the St. Marys River is due to ice cover on the river up-stream from the locks between the lake and the head of the rapids, and that ice jams or ice cover within the rapids occur infrequently, if at all. He finds a measure of the average retardation of outflow from Lake Superior by ice in the fact that the elevation shown by the gage at the head of the rapids for the same stage of Lake Superior averages about 0.13 feet lower in winter than in summer, and that this corresponds to a retardation of the river flow by about 2800 cubic feet per second for these three months, which is about 4 per cent. of the average discharge during this time. When spread over the year, this correction for ice effect would make the average yield only 1 per cent smaller than that computed from the record of elevations by the open season formulas without correction.

St. Clair-Detroit Rivers—Ice Effect

In the earlier years, the precise determination of the discharge during the season when there was no navigation was chiefly of academic interest. Nevertheless, the effect of ice in lessening the discharge of the St. Clair was given much attention by Mr. L. C. Sabin in course of his discharge measurements between 1899 and 1902. Not every winter affords an opportunity for studying an important obstruction by ice. In some winters there is no such obstruction, but during the winter of 1900–01 the ice blockade seems to have been one of the most severe on record.

In the report of the U. S. Chief of Engineers for 1902, page 2819, Mr. Sabin states that in 1901, during February and March, the ice in the St. Clair River, part of the time, covered the surface as far up as the mouth of Black River. For discharge measurements during this period, a section was selected near the foot of the deep, narrow gorge about two miles below the head of the river, within which the surface was not frozen over, by reason of the swift current.

On page 2822 is given a brief description of conditions affecting the winter discharge. The ice that forms along the border of Lake Huron finds its way into the river and proceeds down-stream with the current until stopped where some of the more sluggish reaches have become frozen over. Here, ice accumulates and the obstruction gradually increases and spreads upstream. Partial dams are made, frequently, by floating cakes of ice carried beneath the fixed surface ice. In severely cold weather in course of time an ice bridge is formed across the head of the St. Clair River, which wastes away slowly in the rapids on the down-stream side and is renewed from above.

In 1900, it was late in December before the effect of ice on the discharge was apparent. During January 1901, running ice interferred greatly with discharge measurements at the Dry Dock cross-section and a new measuring station was established in the open water near the rapids. Early in February the ice cover continued up-stream and passed the Dry Dock gage station, covering the river as far up as the mouth of Black River. Thirty-eight discharge measurements were made during February and March. About March 23, the ice broke and the river cleared down to Stag Island, 8.5 miles from the Lake, and later to Algonac, but blocked again early in April and did not become entirely clear of ice until May 8. From March 25 to April 26, conditions varied greatly from day to day. The diagram on page 36 shows the effect on the discharge of the river:

An attempt was made to work out a discharge formula applicable while the river is obstructed by ice, which would give the discharge in terms of the fall in water surface from the Grand Trunk Railway gage to the Dry Dock gage. This formula appears not to have been all that is desirable in precision, or in conditions perfect for its application.

The U. S. Chief of Engineer's Report for 1902, tables 5, 6 and 7, pages 2835-37, gives the results of discharge measurements while the river was partially blocked with ice.

In the Chief of Engineer's report for 1904, page 4106, Assistant Engineer Thomas Russell gives a further discussion of the effect of ice discharge.

In the Warren Report, pages 360 to 364, Mr. Richmond gives a résumé of data on the obstruction caused by ice at each of the Great Lake outlets, which presumably covered his deductions from all of the direct data on file in the office of the Lake Survey. Apparently there was no attempt to utilize indirect data from temperature records, or records of ice cover or ice gorges from files of other observers.

Mr. Richmond reports the St. Clair and the Detroit Rivers are normally covered with ice during the winter months, except in the vicinity of Port Huron and Detroit, where the ice is broken by ferry boats. In addition to the normal ice cover, jams or blockades are of frequent occurrence and at times hold back large quantities of water. Blockades usually form in the Detroit River in late December or early January. These conditions continue into April and occasionally into May. It has been reported that in 1819 and 1840 the St. Clair River was blocked with ice in June.

Each year after the breaking of the blockade in the St. Clair River there is frequently a blockade of short duration in the Detroit River. Simultaneous large blockades in both the St. Clair and Detroit Rivers are not common, but it is seldom that one of the rivers is sufficiently free while the other is blocked, to permit of using its open season equation for accurately estimating the discharge.

From observations made while the river was obstructed by ice in 1901, combined with those made under ice free conditions, an empirical formula has been derived in terms of the fall between the Grand Trunk Railway gage and the gage at the mouth of Black River, which comprises a reach nearly 10,000 feet in length within which the water is rapid and the main channel ordinarily free of ice. It was possible to use this equation during the winters from 1900 to 1906; or so long as the Black River gage was maintained.

For the winters 1900 to 1902, during which the Grand Trunk Railway gage and the gage at the mouth of the Black River were certainly accurate, the retardations of flow for the six months, thus computed from the fall between these gages, averaged 24,500 cubic feet per second.

The Detroit River from Windmill Point to Fort Wayne, although normally covered in part by ice during the winter, is usually free from blockades or ice-jams, and an empirical formula giving the discharge of the Detroit River in terms of these two gages (Windmill Point and Fort Wayne) has been derived. Applying this formula to the gage records from 1906 to 1918 the average retardation during the six winter months appears to have been . . . . 17,600 c.f.s.

Mr. Richmond tried out four different methods for computing the retardation by ice of the outflow from Lake Huron with the following results:

(a)	By G. T. R. and M. B. R. gages, average from 1900 to 1904........	12,200 c.f.s.
(b)	By G. T. R. and M. B. R. gages, average from 1900 to 1909........	9,980 c.f.s.
(c)	By Windmill Point and Ft. Wayne gages, average from 1906 to 1918	8,810 c.f.s.
(d)	From best data from each year, average from 1900 to 1918.......	9,790 c.f.s.
	Mean of the above, average for one entire year........	10,200 c.f.s.

Mr. Richmond drew a general conclusion from the above 18 years, that the average retardation of outflow from Lake Huron due to ice in the St. Clair and Detroit Rivers amounts, for the 12 months, averages about . . 10,000 c.f.s.

He notes that the maximum retardation of flow within the period covered, occurred in April 1918, and for that month averaged . 92,400 c.f.s.
For the five days, April 22 to 26 inclusive the retardation averaged . 115,300 c.f.s.
which was 54% of the normal flow computed from the elevations of water surface meanwhile recorded for Lakes Huron and Erie.

He concludes that the retardation for the average year of 10,000 c.f.s. is distributed in general as follows:

December	6,200 c.f.s.
January	27,500 c.f.s.
February	42,500 c.f.s.
March	28,000 c.f.s.
April	14,300 c.f.s.
May	1,500 c.f.s.
Average for 6 months	20,000 c.f.s.

He notes that this retardation raises Lake Huron and lowers Lake Erie, so that at the time when the ice goes out, Lake Huron has a super-normal elevation and Lake Erie has a sub-normal elevation.

The backing up and increase of elevation in Lake Huron is accomplished in far less time than the draining down. The increased elevation of Lake Huron and the increased fall in the St. Clair and Detroit Rivers causes an increased flow, tending to restore both lakes to normal elevation; but on account of the great area of Lakes Huron and Michigan, a long time is required for the lakes to lose the excess elevation caused by the obstruction of ice in an exceptionally severe winter.

Mr. Richmond estimates (Warren Report, page 362), that in 1918 the retardation of outflow from Lake Huron averaged 92,400 c.f.s. for the entire month of April and for the first five days averaged 115,000 c.f.s. and that to run-off the super-elevation thus caused would take so long that only 90% would be gone at the end of 4 years. In the 10 ice-free months only 32% would be worked off.

In other words, in the ten months following the stoppage, only about 32% of this super-elevation drains off. **It will require about four years to lose 90% of the super-elevation caused by one extremely severe winter like 1901.**

It is a simple matter to compute the rise due the obstructions that were caused by ice during January, February and March to April 30, 1901, as follows:

The total obstruction was equivalent to an average of 74,000 c.f.s. for 105 days, or a total held back of 671,000,000,000 cu. ft.

The combined area of Lakes Michigan and Huron is 45,410 sq. miles or equivalent to 1,268,000,000,000 sq. ft.

The corresponding increase of height of lake caused by choking its outlet, therefore, was . . . . 0.53 feet.

Lake Erie on the other hand has a relatively small area and recovers its normal elevation quicker than does Lakes Huron and Michigan.

In ten months about 93% of the depression in Lake Erie caused by ice in the St. Clair and Detroit Rivers is recovered.

The diagram presented on page 500 showing the great difference in the relative elevations of Lakes Huron and Erie following the winter of 1900, with little ice and winter of 1901 with much ice, are of much interest in this study.

These effects overlap, like a layer of shingles on a roof, four or five in thickness, spaced at equal intervals, with the thin ends forward. In the case of Lakes Huron and Michigan the cumulative effect apparently is to hold the lake about half-a-foot above the level at which it would stand with the same average discharge if there were no ice, for the average retardation due ice of 10,000 c.f.s. corresponds to a height of 0.45 feet on the discharge diagram for Lake Huron, which has an average "increment" per foot of rise or fall..of about 22,000 c.f.s.

More accurate information regarding the daily discharge of the St. Marys, St. Clair and Niagara Rivers during the ice season is urgently needed, particularly at the head of the Niagara River and could be obtained without unreasonable or large expense. A complete cross section gaging is not needed for this; a few measurements at single points near middle of channels would suffice.

Mr. Sabin thus explains in large part the evident change of half a foot more or less in the relative elevations of Huron and Erie which occurred about 1900, by supposing the detentions by ice in the St. Clair River to have relatively been less severe since that time than before, perhaps because of channel enlargements, etc.

Niagara River Discharge

As has been stated on a previous page, the discharge measurements in the St. Marys, St. Clair, Detroit and St. Lawrence Rivers are of only secondary interest in the present studies, in comparison with the records of discharge of the Niagara River, because the Niagara River includes the net yield from all the lakes above and is the site of our chief mass-curve computations for determining the possibilities of water storage.

A few records of gagings near the outlet of the lower Niagara River are found in the Chief of Engineer's Report for 1870, page 568, but the earliest published record of an extensive series of extremely careful discharge measurements, is that found on pages 298 to 321 of the Deep Waterways Report of 1900, forming Appendix No. 7, and dated August 15, 1899. This describes a long series of current meter measurements made from the International bridge, with exceptionally great care.

In the report of Chief of Engineers for 1900, page 5322, Mr. E. E. Haskell reports a continuation of this work, and the verification of the original series of measurements made at the International Bridge, by an independent series made at a cross-section about 1870 ft. downstream; from July to December, 1899. Mr. Shenehon's report under date of July 18, 1900, is found on page 5,326. New refinements for insuring accuracy were introduced as the work progressed. In general, velocities were measured at three-tenths of the depth, as representative of velocities from top to bottom within that vertical section, but also many complete vertical velocity curves were obtained.

In Document 779, Regulation of Lake Erie, 1910, page 34, another account is given of the continuation of the work of these precise Niagara River Discharge Measurements. Mr. E. E. Haskell was in charge from September to December, 1897, and planned the methods. Mr. F. C. Shenehon was in charge from July 1898 to September 1898. Subsequent to the latter date, the gagings by the U. S. Lake Survey were continued under the supervision of Mr. Haskell and Mr. Shenehon.

Probably no discharge measurements of a large river elsewhere in the world have ever been made with such elaborate precautions and such continuous care for obtaining extreme accuracy, as were used here.

The first series of these Niagara measurements was made in 1897 and 1898 from the north side of the International Bridge. The second independent series of measurements was made in 1899, at the "Open Section," located about 1870 ft. downstream; where the cross-section was of different shape, and where the disturbance of currents by riprap around the railroad bridge piers was absent. The open section is described as compact, with well graduated bottom profile. Although its current was reported "absolutely free from eddies", and came from the bridge section on a long straightaway course, with a mean index velocity of about 4.5 ft. per second, it showed a trace of the wake of the bridge piers.

Later, because of doubts cast on the precision of current meter measurement in the deep eddies around the bridge piers at the site of the first measurements, and the possibilities of deep, hidden eddies around boulders on the bottom of the "Open Section," 1,800 feet downstream from the bridge, a third series of current meter measurements were made at the so-called "Split Section" several miles further downstream, below the head of Grand Island, where velocities were still less disturbed, with the result of confirming the discharge curves obtained at the other two sections.

These three series of discharge measurements agreed wonderfully well. The locations are shown in map on page 256, and the results of the velocity measurements are shown in the diagram on page 30.

The meters used were of the Haskell type, with an electric magnetic direction indicator incorporated in the mechanism of some of the instruments.

This use of a meter with a direction indicator at the bridge section, with tests for the direction and swing of the current at great depths, was an excellent precaution for accuracy that has seldom been used. In general, the maximum swing of the current did not exceed 10 degrees, and the velocity measurements were reduced to the plane of the cross-section wherever necessary. This attachment for measuring the direction of the current appears not to have been used in the later measurements.

The Haskell meter has been shown by later tests (see paper by B. F. Groat, in Trans. Am. Soc. C. E., Dec., 1912) to preserve its accuracy in eddying currents better than any other known type. Nevertheless, were it not for this special precaution of the actual determination of the direction of the currents at great depths, there might be more question about the accuracy of individual velocity measurements at great depths at these sections, because of the possible roughness of the river bed, due to the possible presence of boulders dropped by ice, and also because of the riprap around the bridge piers.

The method followed in making a measurement of the river's discharge was that of first determining by means of the current meter, the velocity of the water at ten points at equal intervals between top and bottom, thereby obtaining a vertical curve of distribution of velocity for several vertical sections, from which was determined the relation of the velocity at three-tenths of the distance down from the surface to the average velocity in the entire vertical plane.

These complete curves of velocity in a vertical plane were made at several positions within each bridge span. At intermediate sections the velocity was measured only at the three-tenths depth.

A large number of complete measurements for the cross-section were made during these two seasons of 1897 and 1898, covering a great range in the height of Lake Erie and a corresponding range in the stage of the Niagara River, the height of which is continually varying from winter to summer, and with the direction and force of wind. 72 observations were selected, during which the general conditions of steadiness of height of water surveys through the measurements appeared satisfactory, and where a large variation in elevation or other disturbing cause was evident the measurement was rejected. These several quantity determinations were plotted on cross-section paper and a curve drawn through them averaging the observations by the method of least squares, and although a straight line would have averaged the observations satisfactorily the line was drawn with the slight curvature represented by an ordinary formula for discharge for a submerged weir with a broad crest. The results of these measurements made for the Deep Waterways Board, also those of the following years, all are shown in detail on the diagram on page 30, for the purpose of showing the smallness of the apparent margin of error, and the remarkable agreement of the mean lines for the two very different cross-sections.

Much care also was given to the accurate measurement of the depth in a swift current, by using uncommonly heavy weights supported by a fine steel sounding wire, the inclination of which was frequently measured. The depth of the meter during each velocity measurement was similarly determined with great care.

The relation of the elevation of the river surface at the plane or cross-section of measurement, to the elevation of Lake Erie, was continually observed with much care, and the gagings all reduced to elevation of Lake Erie at Buffalo.

Horizontally, the cross-section of the river was divided into 21 stations and for a complete gaging the velocity was measured within each, in quick succession. The current of five miles per hour, or 7.36 ft. per second, required uncommon precautions to obtain accuracy in measuring the depths. A cast iron sinker was used which weighed 140 pounds suspended by a steel wire about ⅛ inch in diameter.

The discharge diagram resulting from the final adjustment of observations, shown in the diagram on page 30, is one of the most remarkable ever achieved in the gaging of a great, swift-flowing river and reflects great credit on Mr. Haskell, who planned the methods originally, and on Mr. Shenehon, who carried out the details and supervised the daily work. The present writer believes that this series of discharge measurements in the Niagara River represent the world's best achievement in the gaging of a great and swift-flowing river.

The only misgivings which he finds it possible to entertain, pertain to the correctness of the velocity measurement by the meters under the disturbed conditions close to the bottom of the river, which, from his observations on the St. Lawrence, a long way downstream from this site, and also from the conditions found about 15 miles downstream within the unwatered cofferdam upstream from Niagara Falls, he is inclined to believe may have been strewn with boulders and fragments of rock dropped from ice-masses, and therefore uncommonly full of eddies and swirls. These misgivings arise because the writer happens to have had personal experience with the vagaries of current meters in departing from the truth, when used in water with changing currents, violently disturbed by eddies and under the conditions which led to the investigations by Mr. B. F. Groat, referred to above. From the descriptions given, the writer now believes that at most such eddies and turbulence can seriously effect the correctness of the Haskell meter in only the bottom 10 per cent, or 20 per cent, of the section. Fortunately in moderately disturbed currents the Haskell Meter is more correct than most other types, and probably does not under-register more than 3 or 4 per cent within this limited space near the bottom. If so, **the error from turbulence would become almost inappreciable when distributed over the whole cross-section,** or less than one per cent.

The general form of the velocity curves, and the wonderful agreement of the determinations at the three different sections, appear sufficient to set at rest all doubts concerning any important error in the Niagara measurements.

After carefully reviewing the descriptions and studying the rating curves, there can be no question that the data at hand on quantity of water yielded by each of the Great Lakes, month by month for the past sixty-five years at all times when the river is not obstructed by ice, is known with a degree of accuracy sufficient for all purposes of design of regulating works and for accurately estimating and predicting their performance.

The effects of ice, have now been allowed for by constant deductions derived from averages. This method is not satisfactory, but appears about as well as can be done at present. The uncertainty in the estimate of change after making these corrections for ice the same in every year, can not possibly cause serious error in estimating the benefits of regulation in increased elevation of water surface and increased flow in years of small rainfall or small natural discharge. It also leaves no room for important error in the data for estimates of storage and release for maintaining levels and equalizing flow.

Fortunately the obstructions by ice have very much less effect on the discharge of the Niagara River than on the St. Clair.

This general excellence of the Niagara River discharge measurements is particularly fortunate, because as already stated it is upon them that we chiefly rely in estimating the possibilities of regulating, storing and releasing the outflows of the lakes, for the better service to navigation and power development.

Discharge from Lake Ontario

The discharge in the Saint Lawrence River, near Ogdensburg at Point Three-Points, was measured and discharge formulas and rating curves established under the supervision of Mr. Shenehon by similarly careful measurements and practically the same methods followed as in the Niagara River.

APPENDIX NO. 2

ADDITIONAL NOTES UPON DATA FOR ESTIMATING EVAPORATION FROM THE GREAT LAKES

It appears very strange that no direct measurements of evaporation anywhere within the vast extent of the Great Lakes Region from Duluth to Ogdensburg; either in Canada or in the United States;* have been found recorded that have been made within or near the margins of the lakes, by modern accurate methods with large floating tanks, like those now maintained in many water supply reservoirs in the semi-arid regions of the United States; notwithstanding there are numerous Weather Bureau Stations and Lake Survey Offices, water supply intakes and other points on the shores of the Great Lakes where such observations might have been made with satisfactory accuracy and at small expense. (See notes of early estimates, pages 484 A to D.)

One explanation can be found in the general belief, until recently, that there was plenty of water in the Great Lakes for all purposes, and that no precise analysis was needed concerning its sources or its losses; another explanation is that however large or variable this evaporation may be, nothing can be done to change it.

Evaporation is at least a matter of great scientific interest, and a precise knowledge of the causes leading to change in its amount could be of use in future supervision of regulation and adjustment of schedules for storage release.

There are possibilities that the depth evaporated in course of a month, or in a year, varies as widely, almost, as the rainfall; or to an extent hitherto unsuspected.

The time surely will come, in regulation of the Great Lakes for the benefit of navigation and water power, when all important matters of income and outgo will require daily study and a budgetting and forecasting of the supply in each lake, so that gates can be set to best advantage; just as is now done at several of the large water power developments.

The collection of accurate statistics cannot be begun too soon. The total cost involved is relatively small comprising merely,

(1) A few months of experimental laboratory work, with relatively inexpensive apparatus, for obtaining accurate values of the constants in the formulas by means of which evaporation

*A floating tank evaporimeter has been maintained by the Canadian Water Resources Service during the past 13 years, on one of the outlets of the Lake of the Woods, but this is 240 miles northwesterly from Duluth, in a colder and dryer climate.

can be estimated from the standard records at all Weather Bureau Stations, which give the temperature of air and dew point, and the wind velocity.

(2) At each Great Lake, one, or preferably two, evaporation tanks, on opposite sides, one in Canada and one in the States; each preferably 6 or 8 feet in diameter, by 4 or 5 feet deep, of rigid shape, set on a rigid support barely high enough above lake to escape waves, and located on some projecting pier or near the shore of an island.

This tank should have provision for warming the water in winter barely enough to keep an ice sheet from forming, and have a device for slightly agitating the surface. An anemometer should set beside it.

(3) One daily measurement of water temperatures shown by maximum and minimum thermometers in the experimental tank and in the lake, near by should be sufficient, after a few typical days or weeks with self recording instruments, giving complete 24 hour records.

(4) Observations once a day on the depth of evaporation from each tank, supplemented for a few months by an automatic graphical record of depth evaporated, made by an exceedingly sensitive apparatus which preferably would magnify the depth, and be precise to say 0.003 inch.

(5) Comparison for one year of the average wind velocity near shore of lake a few feet above the water surface, with that at the neighboring Weather Bureau Station, preferably by means of instruments which automatically record the total travel and mean direction each hour.

Hope of being of service in this matter of determining the amount of evaporation accurately, and of aiding in regulation of lake levels, were among the chief motives which led the late Professor John F. Hayford into his long years of tedious research for discovering means of measuring with precision the true mean elevation of the entire lake, in spite of it being thrown out of level by wind and seiche.

Failing to find direct measurements of evaporation made by means of floating tanks on the Great Lakes, or any other sort of direct measurement, the writer has estimated the depth evaporated month by month in an average year from each of the Great Lakes by four very different methods as described on pages 80 to 149; for comparison with the direct, but crude, measurements of evaporation obtained by deducting the outflow from the inflow of each lake, described on pages 65 to 79.

Evaporation Data from Floating Tanks

The best data, and practically the only data under climatic conditions similar to those around the Great Lakes, that the writer has been able to find for estimating evaporation are:

(1) Observations of the amount evaporated month by month from small tanks floating in reservoirs of the municipal water supply, at Boston, Mass.

(2) Similar but less satisfactory observations in an extremely small and shallow tank floating in the Mt. Hope Reservoir at Rochester, New York.

(3) Similar observations in a tank in a small shallow reservoir at the University of North Dakota.

(4) Similar observations in a tank at Grand River Lock, Wisconsin.

(5) Observations by the Canadian Hydrographic Service at Lake of the Woods, in a tank floating in an outlet from the lake.

Series Nos. 3 and 4 give only the temperature of air and water and the monthly depth evaporated. Some wet-bulb observations that were made were not worked up. At evaporation tanks for series Nos. 3 and 4 described above, the nearest stations for wind and humidity records are more than 100 miles away.

The Boston-Fitzgerald Observations

The Boston experiments were better than any of the others in scope and in scientific attention to detail and careful verification, but are farther from the Great Lakes than the observations at Rochester. These were made chiefly in a reservoir of the Boston Water Works, about 85 acres in extent, and about 20 feet deep, by Mr. Desmond Fitzgerald, member of American Society of Civil Engineers, during the ten-year period from 1876 to 1886, and are described in the Transactions of the American Society of Civil Engineers for September, 1886, pages 581 to 646, with additional data in the Transactions for 1892, page 275.

The floating tank, in which the most consistent and satisfactory measurements of evaporation were made during the last year of the Fitzgerald series, was ten feet deep and ten feet in diameter, supported by a raft near the center of the 85-acre reservoir, exposed to wind, but protected from the splash of spray from waves. The present writer saw this apparatus when in use. Precautions were taken for precision of measurement, for exposure under natural conditions, and for measuring the effect of each of the following factors separately; (1) Temperature of air, (2) Temperature of water near surface, in tank and in reservoir, (3) Movement of wind, (4) The dew-point temperature of the atmosphere. A graph of typical records is shown on page 481.

Unfortunately, no anemometer was set directly beside the floating evaporation tank. Wind movement was measured at a station on shore, 30 feet above the ground, and it was assumed from a few comparisons that the wind velocity at the floating tank was ⅓ that at the elevated anemometer on shore. This ratio is open to serious question. General experience, and formulas in common use by meteorologists for estimating the relative velocities at various heights in nearly the same vertical line, give a velocity of wind near the surface 82% of that measured at a height of 50 feet above, instead of the 33% used by Mr. Fitzgerald.

The autographic register devised by Mr. Fitzgerald for measuring evaporation continuously for a week without interruption, was the best piece of apparatus ever set up for this purpose, so far as known.

Deep tanks and shallow tanks were compared side by side. Similar tanks were exposed, one to the sun and the other in the shade, and comparisons were made with results obtained from small tanks near one of the large tanks, and with the evaporation from an unused reservoir in Boston about one acre in extent, measured by lowering of surface.

The observations on these floating tanks also were confirmed during a period of three rainless weeks in summer, by comparison with loss in an adjacent 37.5-acre division of the reservoir, to which inlet and outlet values were meanwhile closed.

A close analysis shows that various features of this experimental work at Boston could now be improved upon by extending its range, but this was pioneer work of its kind, and nothing better has yet been done under similar climatic conditions, and **nothing nearly so good east of Colorado and Texas, in the 40 years since these experiments and observations were made.**

The greatest value of the Fitzgerald research lies in its finding a close relation between the mean monthly temperature of the air and the depth of water evaporated, and not in its attempt to derive a formula for hourly evaporation, based on vapor pressures and wind movements.

Features of special value in these Fitzgerald researches are:

(1) The comparison of observations on tanks or various sizes, up to 10 feet diameter.

(2) The excellent autographic register of evaporation from a 10-foot tank floating in the reservoir.

(3) The confirmation of tank experiments, by observation on the old Beacon Hill reservoir, of nearly an acre in extent, carried on for several years.

(4) Confirmation by three weeks of observation on a division of the Chestnut Hill reservoir 37.5 acres in extent, during which time no rain fell and inlet and outlet valves were closed.

(5) Confirmation by records of the best observations made elsewhere.

(6) Two elaborate series of laboratory experiments on evaporation, were made for confirming the relation of rate of evaporation to (V-v) in Dalton's law, and for discovering the value of the wind factor.

In these laboratory experiments the water was heated to various amounts above atmospheric temperature by means of a water bath surrounding the evaporation pan which was 1 inch deep and about 15 inches diameter. Possibly this arrangement set up air currents which aided escape of vapor and increased the evaporation above that normal for this temperature.

Mr. Fitzgerald recognized that the forces tending to cause evaporation vary greatly from hour to hour, and tried to establish a general formula for the depth of evaporation in each hour, in terms of vapor pressures corresponding to temperatures of water and dew-point, coupled with wind movements.

He was not successful in establishing his formula, but he laid the foundations for a far simpler and more practical method of estimating evaporation, by observing, after all of this experimenting, that the total depth of evaporation month by month varied in remarkably close relation to the mean temperature of the air for that month as measured at the nearest U. S. Weather Bureau Station. This is shown by the cut on page 103.

Fitzgerald Observations on Winter Evaporation

We have Mr. Fitzgerald's opinion (based on his formula) that on one day, when he saw open water at 37° F. "steaming" into extremely cold air (at 12° F.), that evaporation was proceeding at the rate of 0.23 inches per 24 hours, which, if continued one month would amount to 7 inches.

Although Mr. Fitzgerald made laboratory experiments which at their upper limits went far beyond water temperatures found in natural lakes, **he did not get down experimentally to the condition found on the Great Lakes, of water at 32 degrees in contact with currents of much cooler air.** He did, however, experiment on the evaporation from the surface of ice and snow into air, and says that he **found the Dalton law was followed at these low temperatures.**

In the chief series of experiments on evaporation from a surface of snow made by Mr. Fitzgerald through the winter of 1875, he reports (page 610) a general result of 0.02 inches per day for the winter's average. This is equivalent to 0.60 inches evaporated per month. He found the **evaporation from a surface of ice about double that from snow.** This would amount to 1.2 inches per month, from ice.

Mr. Fitzgerald's experiments in this field of precise measurement of evaporation from surfaces of snow and ice, although leaving much to be desired, are the best yet known to the writer.

After much consideration of his experimental data, Mr. Fitzgerald adopted for average winter values, in the Boston climate, of inches depth of evaporation loss per month: December 1.2 inches, January 0.9 inches, February 1.2 inches, March 1.8 inches, and considered these approximations, if in error, probably less than the actual.

He found that ice over a reservoir maintained a more uniform temperature in extremely cold weather, than a detached block of ice in the open air; the evaporation loss from which, measured by weight, was under experiment. For example:

On an extremely cold day, January 12, 1875, with air averaging from —4.9° to +6.1° F., he found the ice over the reservoir about 14° to 10° warmer than the air, the temperature of the ice being influenced by the temperature of the mass of water beneath. On the preceding day, which was somewhat warmer, the ice on the reservoir was at 22° F., while air averaged 16° F.; and on both days his experimental block of ice followed the air temperature much more closely than the ice covering the reservoir, being only 1° F. higher temperature than the adjacent air.

In two experiments, where the records mention no wind, the block of ice showed evaporation losses of from 0.06 inch per day to 0.04 inch depth per day; equivalent to respectively 1.8 and 1.2 inches loss per month, with air temperatures probably mostly between 20° F. and 30° F.; and on one occasion, February 24, 1886, with a wind of 12 miles per hour he found an evaporation loss from ice at rate of 0.2 inch per day. Apparently he considered these few careful experiments on evaporation loss from ice illustrative, rather than conclusive.

By several brief experiments on blocks of ice he found that **his formula for depth of evaporation, based on the Dalton law of differences in vapor pressures deduced from summer conditions, was fairly accurate in its application, to vapor pressure differences at these low winter temperatures.**

Wide Variation in Evaporation on Successive Days

Reference has been made, on page 81, to large changes in rate of evaporation. The best data in all this region giving precise measurements of change in rate of evaporation from day to day, are those by Mr. Desmond Fitzgerald;* published on page 598 of the Transactions of the Am. Soc. C. E. for 1886. These precise autographic measurements on a 10-foot tank near the middle of an 85-acre reservoir show variations of from 4 to 1; in this ratio, or from more than double the mean monthly rate of evaporation on a Monday; to less than half this mean rate upon Saturday, all within the space of 6 days. In other words, within the same week and in the absence of rain there was four times as much evaporated in one day, as in another.

In this case, relative humidity and wind seem to have been the chief controlling variables. Vapor pressure differences, express the control more precisely than relative humidity, because of taking account of temperatures of both air and water, and of moisture already present in the air; but relative humidity is a popular term and better understood, and is easily used in the computations, since the dew-point temperature, although not given in the published record, can be readily found by means of standard meteorological tables, from the given relative humidity and air temperature.

There appears to be no good reason why large variations from day to day, similar to those found at Boston, may not

*The present writer believes from personal recollections and, after conference with Mr. Fitzgerald, that much more data could be obtained from these records, than was given in the publication above referred to; and has tried in vain to get access to the original voluminous papers. They were carefully preserved for a time, but now appear to have been buried beyond discovery, in course of 40 years changes in occupancy of buildings, among other accumulations.

occur on the Great Lakes, under such widespread differences in relative humidity and force of wind as come with a shift from a dry north wind to a warm, moist wind from the south.

Mr. Fitzgerald's excellent autographic apparatus gave the following depths evaporated from his 10-foot tank. The first day of his published series happened to give the largest depth of evaporation that he had ever measured, and was notable for its low relative humidity. He believed that this day's observation gave as great a depth of evaporation as ever likely to be found in New England, namely, about one-half inch in one day.

The chief factors controlling this change in rate of evaporation are given in the table below, so far as known. The figures for temperature, humidity, and wind, are 24-hour mean values from 5 p. m. of one day to 5 p. m. of the next.

The U. S. Weather Bureau observations (marked "W. B.") in table below were taken at the U. S. Weather Bureau Station (then called the "U. S. Signal Service"), on top of the Boston Post Office Building, five miles nearer the sea, where the temperature of air has been found in summer to average about one degree cooler than at the reservoir.

Date June, 1885 24 Hours 5 p. m. to 5 p. m.	Inches Depth Evaporation in 24 hours	Relative Humidity		Wind Miles per Hour		Temperature of Air		Temperature of Water		Difference in Vapor Pressure V-v	
		At W. B. *	At Res.	At W. B. *	At Res.	At W. B. *	At Res.	In Tank	In Res.	At W. B.	At Res.
Mon. 22–23	0.540	....	....	....	....	....	....	....	....	....	....
Tues. 23–24	0.420	39.7	50.0	17.0	11.9	66.3	64.5	69.0	70.0	0.448	0.404
Wed. 24–25	0.270	51.6	60.5	18.6	7.2	71.6	70.2	70.2	70.1	0.338	0.291
Thurs. 25–26	0.210	58.7	....	13.3	....	74.0	....	74.9x	72.2x	0.372	....
Fri. 26–27	0.190	71.0	....	11.0	....	71.6	....	74.8x	73.1x	0.311	....
Sat. 27–28	0.140	76.3	....	12.0	....	72.3	....	74.4x	74.1x	0.245	....

xAverage 24-hour daily means 12 p. m. to 12 p. m., used for June 26, 27 and 28.

*Values representing Weather Bureau observations at Boston are averages of three daily readings taken at 11 p. m., 7 a. m. and 3 p. m.

The relative humidity at site of the evaporation observations is seen to have been decidedly higher than at the U. S. Weather Bureau Station. The wind at reservoir, 30 ft. above ground, on these 2 days averaged respectively, 70% and 39% of that as observed at the U. S. Weather Bureau Station. In general this ratio was 70%. Where no figures are given (but marked"....."), data were not available.

At the beginning of this week, on Monday, June 22, 1885, the weather was clear, cool and the air dry, with wind from the northwest where it remained for 3 days. The wind then shifted into the west where it remained for 2 days, and then it again shifted into the southwest and east, when rain followed on Sunday, the 28th, with increase in relative humidity of air.

This week presented extreme conditions, but cycles of change in wind, in weather, and in relative humidity, similar to the above, are not uncommon, either in New England or in the Great Lakes region.

The Rochester Observations

The Rochester observations were instituted 34 years ago by the eminent hydraulic engineer, Mr. Emil Kuichling and have been continued with much care to the present time. These are made in a shallow tank of about 15 inches diameter, 6 inches deep, made of indurated wood fiber, containing about 3 inches depth of water, floated within a raft in an elevated distribution reservoir, about 15 feet from the shore and from 5 to 10 feet below the sloping earth embankment.

The reservoir is from 14 to 16 feet deep and about 750 feet long by 300 feet wide. The tank is about 13 feet from its west shore. Observations of evaporation from snow and ice, by loss of weight, are continued with care through the winter.

The small size of the floating tub at Rochester is to be regretted, but may be explained by these observations also having been begun as pioneer work by the late Emil Kuichling, years before the influence of size of tank upon depth evaporated was understood. This same size of tank has been continued for comparative purposes.

The non-conducting quality of the indurated fiber and the shallow depth of water in the tank, tend to differences in temperature of water in the tank and in the reservoir.

It is to be hoped that a rigid iron tank 5 or 10 feet in diameter, and 5 feet deep may be placed alongside for a few years of comparisons, and then become the chief feature; for these Rochester records date back the farthest of any in the lake region, and have been admirably supported by the many other climatic data continuously observed close by.

It is worthy of note that the temperature of the water surface in this Rochester distributing reservoir, which holds only about a day's supply, is influenced by the circulation and constant renewal of water by conduit from Hemlock Lake. This reservoir freezes over and thenceforth the temperature of its surface water must be 32° in winter.

The small shallow evaporation tank probably freezes over sooner than the reservoir, and thereafter the evaporation recorded is that from a surface of ice or snow.

North Dakota Observations

The data for evaporation at the University of North Dakota are taken from U. S. Geological Survey Water Supply Papers for Upper Mississippi and Lower Hudson Bay Region.

The evaporation gage at University of North Dakotà was established April 17, 1905, and observations were continued until June 15, 1920. The gage consisted of a heavy galvanized iron tank, three feet square and 18 inches deep, placed in the center of a raft, anchored in a pool formed by flooding a little valley, which at extreme low stage has a central depth of about 6 feet, and an area of at least 8,000 sq. ft.

The temperature of water and air, and amount of water evaporated were observed daily about half an hour before sunset, as it was found that at that time of day there was rarely a perceptible difference in the temperature of the water within and without the tank.

No records of observations of dew-point temperature, or of relative humidity, are now available from this station.

In the years 1905 and 1906 the air temperatures are not daily means but merely the temperatures at the hour of observation (usually six or seven p. m.), and are not consistent, since the time of observation varied slightly.

The air temperatures for 1907 and after, are daily means as recorded by self-recording maximum and minimum thermometers.

Wisconsin Observations at Grand River Lock

The data on evaporation at Grand River Lock are taken from the Report of the Consulting Engineers on the Lake of the Woods Investigation, published under the direction of the International Joint Commission.

The Grand River Lock station is located on the Upper Fox River, Wisconsin. The equipment consists of a standard pan, 3 feet square, supported in a raft in a shallow slough of water near the Lock. Observations were made twice daily, under the direction of Mr. L. M. Mann, U. S. Assistant Engineer, Oshkosh, Wisconsin.

This station was established in 1905 and discontinued in 1918. The data observed included temperatures of air and water, depth of evaporation, and precipitation.

No measurements of relative humidity or dew-point were made.

In April and November particularly, where the observations covered a part of the month only, the value for evaporation for the whole month was obtained by assuming that the observed daily rate at the given temperature continued for a full month. This assumption makes the mean temperature and the depth of evaporation too large, due to the fact that the portion of the month for which no records were secured was the colder part.

Lake of The Woods Observations

The observations on evaporation at Lake of the Woods have been maintained at Keewatin since 1913, as part of the regular work of a meteorological observatory of the Canadian Water Resources Branch of the Dominion Water Power and Reclamation Service. This station comprises a thermograph, barograph, wet and dry-bulb thermometers, anemometer, maximum and minimum thermometers, and a tank 3 feet square, set in a small bay on the north shore of the lake, a short distance upstream from one of its main outlets, in a position that appears to insure circulation.

The wind gage is located on top of a large grain elevator at about 150 or 175 feet above the lake surface.

The psychrometer is of the wet and dry-bulb variety, swung by hand. The operator always faces the wind.

Evaporation is measured by cups of water, put in or taken out until the tank level is precisely at top of a pointed brass rod in its center. The cup holds the equivalent of 0.01 inch in depth of tank.

The evaporation recorded after a gap in the record is for only the preceding day.

When tank and lake freeze over, observations on evaporation are discontinued until open water of the next Spring.

In winter, this outlet from the lake may draw a mixture of deep water and surface water, at a temperature averaging slightly above that of the surface water of the lake. The lake is said to be about 100 feet deep on this northerly side although only 50 feet deep over much of its area and only about 20 feet deep near the southerly side; and thus, while depth of lake near this tank and of water in circulation are far greater than at either of the other reservoirs at which evaporation has been measured, the condition at Keewatin is notably different from Lake Superior; which has depths of 1,000 feet.

This greater depth of Lake of the Woods as compared with the other reservoirs in which the floating tanks set, that are used for data, at first view suggests that its records be given greater weight. Further consideration shows reasons to the contrary, chief among which are: the intense cold of the winter climate, a relative humidity averaging much lower than around the Great Lakes, and certain other features that appear somewhat abnormal. A study of the daily records of depth evaporated, shows non-concurrence with temperature and humidity factors in many cases. While the Lake of the Woods data have been given some weight in drawing the "average" lines in the diagrams showing the relation of monthly depth of evaporation to monthly average air and water temperatures, they have not been allowed to outweigh that from the other data stations.

The evaporation at Keewatin when temperatures are falling during the later half of the year, or from August to December, is much larger than that observed at precisely the same temperature of air while the temperatures are rising, from April to July.

The reverse form of cycle is found at all other evaporation stations where climatic conditions are fairly comparable, at Boston, Rochester, North Dakota and Grand River Lock, at each of which the evaporation is larger in the early half of the year, while temperatures are rising, due to the shallowness of the reservoirs and the fact that the temperature of the water follows closely that of the air, while rising during the spring and early summer and while falling during the late summer and autumn.

Evaporation Investigations by Professor L. G. Carpenter at Fort Collins, Colorado, 1895–1897

The results of Professor Carpenter's experiments are published in a bulletin of the Colorado Agricultural Experiment Station, comprising 32 pages, under the title, "Loss from Reservoirs by Seepage and Evaporation."

These observations were made near Fort Collins, Colorado, at about 5,000 feet above sea level.

They give little help in estimating the evaporation from the Great Lakes, or in determining the vapor pressure factor, or the wind factor, in a general formula for evaporation, because of lack of detail, also because of the small size of tanks, which were only 1 foot square, and because the water level in these small evaporation tanks was held at about 4 inches below their tops, permitting a vapor blanket, or blanket of air chilled by the act of vaporization, to obstruct evaporation.

Moreover, the rain gage and the wind gage to which these observations were referred, were several miles away from the evaporation tanks.

There was no dew-point determination. The altitude, being about 5,000 feet higher than at Boston, might be expected to give larger evaporation than at Boston or than at the Great Lakes.

Nevertheless, these experiments by Professor Carpenter have been of special interest because his formula derived from them, in spite of all the differences in circumstances, give constants which agree closely with those derived by Mr. Fitzgerald.

The Fort Collins series comprises several series of observations; one covering a period of ten years from 1887 to 1897, from a tank **imbedded in the ground,** which tank was three feet square, and two feet deep at first; but for the last eight years, three feet deep.

The water surface ordinarily was four inches below the rim of the tank and thus formed a pocket, which, with light winds, may not have been well freed from vapor.

Observations **on floating tanks** 1.0 foot square were made only during the two years (1896–1897), at three places.

(1) At Lee Lake, a small reservoir about 4 miles from the college, which reservoir was shallow and exposed to the wind, and in which weeds grew freely, with water varying from 6 feet to 10 feet in depth during the season.

(2) At Loomis Lake, a little over a mile west from the college, in which the depth varied from 5 to 10 feet, and which is free from weeds.

(3) At Claymore Lake, 6 miles northwest of the college. This has a sort of wind-screen to the westward, consisting of a ledge of sandstone about 400 feet high, rising at an angle of 20 degrees, which interferes slightly with the wind, and probably lessens evaporation a little. The depth varies from 6 to 15 feet.

Observations were made once a week in 1896, and semi-weekly in 1897, by measuring from across the top of the tank down to the surface with a rule graduated to tenths of inches. The average depth of water below the top was from 3 to 4 inches.

Because of the small area of these tanks (1 foot square), and the depth of this pocket, a vapor blanket, may have interferred with freedom of evaporation to an important extent.

Correction for rainfall was made by deducting the amount measured in the rain gage at the college, several miles away.

The wind, also, was measured at the college **several miles away,** by an anemometer **on a tower 60 feet above the ground,** with some trees at moderate distance.

The evaporation, month by month, was found greater at these floating tanks one foot square, than at the 3-foot tank embedded in earth at the college grounds. This was supposed to be a result of their greater exposure to the wind, and the fact that they were agitated by waves, and **a film of water left adhering to the metal sides with every movement, which film added materially to the evaporating area.**

Mr. Carpenter's final adjustment gave as the annual evaporation for that locality, 59.5 inches.

One important feature of these Fort Collins' records is the discovery, by comparing the average of the 7 a. m. and 7 p. m. water temperature observations with the mean temperature shown by hourly readings, that the **average of the hourly observations was higher by about 3.5 degrees than the average of the two observations at 7 a. m. and 7 p. m.,** due to the fact that while heating, the surface of the water heats rapidly and the lower layers slowly, but in cooling the mass of water cools as a whole.

The mean of the maximum and minimum temperatures was found much closer to the true average, than the average of the two observations at 7 a. m. and 7 p. m.

Effect of Agitating Surface

Regarding the effect of agitation, an interesting reference is made in this report by Professor Carpenter, to the report of a French engineer, Mr. Maurice Aymard, who found by four day's observations on two tanks 20 inches in diameter and two feet high, in one of which the water was still, while in the other it was kept in agitation by a disk with holes, that was slowly raised and lowered, that **when water was agitated the loss by evaporation was found to be one-third more than in quiet water.**

EFFECT ON EVAPORATION FROM THE GREAT LAKES OF A CHANGE IN TEMPERATURE OF THE WATER SURFACES OR AIR

(1) If the water temperature during the five summer months (May to September inclusive) should be higher than that determined and used in computations by John R. Freeman, the total quantities evaporated during the period from the different lakes would be changed as per table below. It is assumed that the temperatures for April and October are correct as used.

Lake	Evaporation as Computed by J. R. F.	Evaporation if Water Temperature is 1° Higher	Increase in Evaporation Due 1° Increase in Water Temperature
	Inches	Inches	Inches
Superior	2.95	3.08	0.13
Michigan-Huron	12.22	12.67	0.45
Erie	23.75	24.62	0.87

(2) If the air temperature as used by J. R. Freeman during the five winter months (November to March, inclusive) be lowered 1° F., the following changes in total evaporation for the period would be found.

Lake	Evaporation as Computed by J. R. F.	Evaporation if Air Temperature Were 1° Lower	Increase in Evaporation due 1° Decrease in Air Temperature
	Inches	Inches	Inches
Superior	15.41	15.98	0.57
Michigan-Huron	12.95	13.77	0.82
Erie	11.43	12.39	0.96

(3) The effect on the yearly evaporation from each lake if **water during summer is assumed 1° warmer,** and **air during winter is assumed 1° cooler,** and temperatures for both air and water for April and October are not changed, would be as follows:

Lake	Yearly Evaporation as Computed by J. R. F.	Yearly Evaporation with Changes in Temperature as Given Above	Change in Evaporation Due Increase of Water Temperature in Summer and Decrease of Air Temperature in Winter by 1° F.
	Inches	Inches	
Superior	22.15	22.85	+0.70
Michigan-Huron	29.12	30.39	+1.27
Erie	41.88	43.71	+1.93

Observations on Evaporation by U. S. Dept. of Agriculture at South Denver, Colorado

The excellent monograph, published in the "Journal of Agricultural Research", by Mr. R. B. Sleight, Assistant Irrigation Engineer (now or recently at the University of Minnesota), July 30, 1917, upon the evaporation from the surfaces of water and river bed materials, gives the best data that have yet been published for comparison between land tanks and floating tanks, and tanks of different sizes. These experiments were devised to give data for local use, or for use in a climate like that around Denver. No attempt was made to develop a formula of general application.

These data are useful in the present study, mainly for judging of the effect of differences of exposure and size of tanks, because altitude, dryness of air, radiation at night into a clear sky, and general climatic conditions at Denver, Colorado, where these experiments were made, differ greatly from the conditions found around the Great Lakes.

Data from many floating tanks in reservoirs in California, and in various parts of the semi-arid states, giving the total inches evaporated month by month, without the attendant data on temperatures, dew-point and wind, also are available, but have not been used because of the writer's experience, and his belief in the possibility of serious error resulting from use of data on evaporation observed under a very different climate.

This Denver series was of such uncommon excellence, so far as it went, that it merits a brief description. These experiments upon evaporation from tanks on land were made in the Irrigation Field Laboratory, at a locality in South Denver about 5340 feet above sea level, in an open prairie where the only buildings near were a few scattering, low bungalows, several hundred feet distant or so far removed that they could not in any way affect the free movement of the wind at the evaporation tanks.

The tanks and other apparatus were provided especially for these experiments. More than twenty evaporation tanks were used, varying from one foot to twelve feet in diameter; round, square and oblong, and varying in depth from six inches to three feet, but all having their water surface ordinarily three inches below the top.

All of these evaporation tanks were made of galvanized sheet iron, and nearly all were set into the ground with only three inches of the top exposed, or so that the water surface was very nearly level with the ground.

One of the standard U. S. Weather Bureau pattern tanks, 4-feet diameter by 8 inches deep, was set wholly above ground.

One floating evaporation tank of the standard type of the United States Geological Survey, three feet square by three feet deep, was set near the middle of a little lake about 550 feet wide x 1300 feet long.

Depths were measured by hook gages at all tanks but one, in which a continuous recorder was used.

A remarkably complete outfit of meteorological instruments was provided, all of the standard Weather Bureau type. This comprised three anemometers, whirling and sling psychrometers, a Piché evaporimeter, maximum and minimum thermometers for both air and water, also a thermograph, a recording psychrometer, a barograph and a standard barometer.

One anemometer was on a 14-foot tower, another had cups set at two feet above the ground, and the third, near the floating tank, had its cups two feet above the water.

Four rain gages were in use, three at the Laboratory and one at the lake. Water temperatures were obtained with maximum and minimum thermometers, with bulbs immersed 0.05 feet below the surface.

Observations were begun November 1, 1915, and continued about one year, until the end of the season in 1916.

The standard rules and practice of the United States Weather Bureau were carefully followed in observing data, and the personal equation in observation was eliminated as far as practicable.

From the admirably full and clear description, of 52 pages, in the Journal of Agricultural Research, there can be little doubt that this series is in many particulars the best of its kind ever made; but its purpose plainly was to give practical results useful in regions with a climate like that of Denver, and not for establishing formulas or the constants in the physical laws of evaporation.

It is to be regretted that the published report does not contain a more complete record of the temperatures of air, water and dew-point, and also of the wind movement.

RESULTS:

An excellent comparison was obtained upon the rate of evaporation from tanks of different diameters, using a 12-foot tank as the standard, and all tanks being imbedded in the ground with rim projecting three inches, so the water surface was level with the ground outside, water being 2.75 feet deep. All tanks were made of galvanized sheet iron. The smaller tanks gave larger rates of evaporation. A curve of relation was worked out from which the following ratios of increase are taken.

Diameter of Tank	Evaporation Compared with 12-ft. tank
12 feet	100.0%
10 "	100.4
9 "	101.0
8 "	102.8
7 "	106.0
6 "	109.5
5 "	113.5
4 "	118.0
3 "	123.0
2 "	128.8
1 "	155.0

The reason for the excess of evaporation from the smaller tank was found in the evaporation of the thin film drawn up by capilarity around the metal rim of the tank, or thrown up by wave action caused by the wind. The effect of the heat absorbed in the metal strip projecting above the ground is obviously twelve times as great, relatively, for the tank 1 ft. diameter, as for the tank 12 feet in diameter. It was noted that although the area of the wet strip caused by capilarity was relatively twelve times as great for the smaller tank, this was compensated to some undetermined extent by the higher waves in the larger tank.

The possible effect of a low thin vapor blanket over, or within, the top of tank, in decreasing evaporation was mentioned; but no definite conclusions expressed regarding its percentage effect. (A thin film of air chilled by process of vaporation and not quickly dislodged from this pocket by the wind, would have the same effect of retarding evaporation.)

By comparison of tanks three feet square with round tanks of similar area, it was concluded that the square tank gave increased evaporation because of the greater rim area, in the ratio of about 4.8% excess.

Comparison was made between deep tanks with water 5.75 feet deep, and shallow tanks with depths to 0.25 foot.

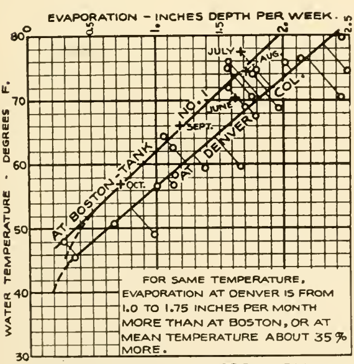
Nine tanks in this series, were compared between May and November. The differences in evaporation appeared plainly due to differences in amount of heat absorbed by the water. The shallow tanks showed the greater evaporation in the earlier months, when cooling at night was greater. Later, in mid-summer, with a greater range in water temperatures from day to night, the shallow tanks gave the lesser evaporation. The difference was not great, but the conclusion was reached that **no less depth than two feet should be used.**

The difference between the evaporation from a tank 6 ft. deep and one 3 ft. deep was found so small that no advantage was to be had in a greater depth than 3 feet.

The range of mean air temperatures by maximum and minimum thermometers during the four months was from 61° F. up to 73° and down to 50°.

Experiments on evaporation from water kept in slow circulation by a pump, with surface velocities from 0.5 ft. to 1.25 ft. per second, were found about **seven to eight per cent larger than from still water under similar conditions.** No difference in evaporation was measurable as between the higher and the lower velocity of the water.

The effect of increase of temperature in increase in depth of evaporation within a full week's time, was measured by comparing several tanks, two feet diameter and 1 ft. deep, in which water had different temperatures; apparently attributing the entire effect to temperature of the water surface, **without any particular attention to dew-point or wind** (which omissions are unfortunate), and a series of observations was obtained which scatter relatively little from the mean curve. The increase of temperature was obtained by inserting electric light bulbs in the water.



COMPARISON OF EVAPORATION AT DENVER, COL. AND BOSTON, MASS. FOR SAME MEAN TEMPERATURE OF WATER.

This curve (Figure 5, Data from Table VIII) is reproduced along with a mean curve from the Fitzgerald experiments on tank No. 1, in which the various water temperatures were those coming naturally from the temperature of the air, as the season advanced.

Comparison was made between the Standard Weather Bureau tank of 4 ft. diameter and 8 inches depth of water, made of galvanized sheet iron and fully exposed to air except on its bottom, with a tank 12 ft. diameter with water 2.75 ft. deep. These comparisons—with measurements of weekly depth evaporated from each from November 22, 1915 to November 13, 1916, or a full year—showed **50 percent excess evaporation from the Standard Weather Bureau tank** over that from a tank 12 ft. diameter with water 2.75 ft. deep, buried in sand to a line level with the water inside.

(It is hard to understand why the Weather Bureau continues such a tank in use as its standard, when a larger and deeper tank, with base and outside thoroughly insulated from sun and wind, would give results so much more comparable with natural reservoir conditions.)

Comparison of a standard U. S. Geological Survey floating tank 3 ft. square by 1.5 ft. deep, was made with the 12-ft. diameter land pan three feet deep. **The smal-**

ler floating tank was found to give an excess of 8.9% for the seasons. (This may have been due to wave motion wetting the sides so as to present a large area for evaporation.)

This floating tank gave 86.1% of the evaporation from a precisely similar tank buried in the ground, so that the water inside was level with the ground outside.

Although the wind velocity was measured, no attempt was made to determine the relation of increase of wind velocity to increase of evaporation, and no attempt was made to establish a formula, lest it be used beyond the limits of these experiments.

The unit of time in measuring the depth of evaporation was one week, and the various records give the means of the water temperatures and of the wind velocities for each week, during the entire run of each series—comprising in some cases a few weeks and in other cases about a year.

The records of mean dew-point temperatures and air temperatures were apparently preserved but are not published.

To one familiar with the Denver climate, it is obvious that within each 24 hours there is an extremely wide range in temperature, relative humidity and wind. The clear dry air gives a large daily temperature range, from the results of insolation by day and from extremely large radiation loss at night, unknown to any similar extent in the Great Lakes region.

Various climatic causes combine to produce more than double the annual evaporation at Denver, in comparison with that resulting from the very different climatic conditions around the Great Lakes.

ADDITIONAL NOTES ON STUDIES OF EVAPORATION MADE FOR THE U. S. WEATHER BUREAU

By Professor Frank H. Bigelow

The most elaborate series of investigations upon evaporation that have been made during the past 25 years, were those made for the U. S. Weather Bureau by Professor Bigelow, following the outbreak of the Colorado River into the Salton Sea about 20 years ago, and it may be well to explain why it has not been possible to make more use of them in the present study, and how the Bigelow series of experiments came to be made.

The probable time that would be required, after the break was closed, for the evaporation of this great body of water contained in the "Salton Sea," interested the U. S. Reclamation Service, the U. S. Geological Survey and the U. S. Weather Bureau, so that a Board of Conference was sent to the Salton Sea to examine the feasilbility of undertaking a campaign of study on evaporation.

While these studies were in progress an interesting series of papers were published in the Monthly Weather Review by Professor Frank H. Bigelow; and Mr. C. E. Grunsky, then Consulting Engineer to the U. S. Reclamation Service and contributing to the studies, also reported upon the conditions found.

Professor Bigelow's first report was in the Review of July 1907, and this described the scope of the proposed study, with an excellent brief review of previous researches and formulas, and a theoretical study of the probable laws of evaporation, from the view point of thermodynamics and the kinetic theory of gases. Professor Bigelow was exceptionally expert in mathematical analysis, and appears to have approached the problem more from that background, than from that of an experimental physicist familiar with the difficulties of making precise measurements of some exceedingly minute changes in an unstable water surface, in an open field far from laboratory facilities.

In the Review of February 1908, he made further report regarding the progress and gave a résumé of the data obtained in preliminary researches at Reno, Nevada, from August 1 to September 15, 1907. These comprised an extensive series of preliminary measurements of evaporation from a series of shallow pans on 5 towers, each about 45 feet in height. Evaporating pans, mostly 6 inches deep and 2 feet in diameter, were placed at various levels exposed to the air all around. Other evaporating pans 6 feet diameter by 8 inches deep were placed on the ground, or partially immersed, one at the base of each tower.

The 5 towers were set at intervals of about 400 feet, on a straight line crossing a city water supply reservoir of trapezoidal shape, about 800 feet across. One of the towers was placed near the middle of the reservoir, while two were on its shores, and the other two were each about 440 feet distant from the reservoir, one on dry land and the other in an irrigated field of alfalfa.

Systematic measurements of wind velocity, air temperature, water temperature and temperature of the dew-point, were made, all at three-hour intervals, day and night, and the series promised a great addition to knowledge of the laws of evaporation, which promise was not fulfilled, because of various difficulties which gradually developed.

These observations and deductions of Professor Bigelow are described in the Monthly Weather Review for February 1908, 1910 and July 1910, also in the Weather Review Summary for 1908, and are briefly discussed by Professor C. F. Marvin in the Monthly Weather Review for February 1909.

The chief obstacles to success appear to have been:

(1) Lack of methods or devices for avoiding confusion of causes, or for separating the temperature effect from the wind effect.

(2) Lack of sufficient precision of measurement of depth of evaporation, inherent in the apparatus employed.

(3) Too much attention to the theory along lines of thermodynamics and kinetic theory of gases, and too little attention to precision in measuring the actual evaporation within each 3-hour interval.

(4) Too much reliance upon mean values, deduced by methods of least squares, from a multitude of somewhat discordant observations.

The tables of rates of evaporation determined from measurements at intervals of three hours and carried out in averages to three places of decimals, or thousandths of a millimeter, lose their interest after one discovers that the apparatus for making the individual measurements of depth of evaporation at ends of three-hour periods, were indefinite to half or quarter of a millimeter, or to a larger extent than the total evaporation within this three-hour period.

Professor Marvin, while discussing these Bigelow observations for evaporation, in course of developing the "Marvin formula" says:

"The discordancies are, so far as the writer can see, fundamental and unequivocal. Unfortunately, the original observations are not conveniently available, and the present material has been built up very extensively by processes of both extrapolation and interpolation. In fact, a large part of it must be regarded as hypothetical." . . .

"There seems to have been no failure whatever to observe regularly at Reno all the meteorological elements that we imagine influence evaporation in every way. We are, therefore, compelled to adopt the view that the actual conditions must differ in some systematic way from the observations . . . The pans exposed in the free air are relatively much more freely exposed, even in light winds, than the pans floating low in a great sheet of water, especially when we bear in mind that the floating pans are extensively surrounded by a floating raft and breakwater system designed with the specific object of checking wind and wave influences.

"It seems likely that the vapor sheet over the floating pans must really have been less disturbed by the wind, and had a greater density, than in the case of the pans more freely exposed."

Professor Marvin says, most appropriately; relative to deriving formulas for evaporation:

"It is hardly worth while to speculate on the details of this problem until we get a sufficient number of exact observations giving us the unequivocal facts upon which we can build."

An excellent review and comparison of some of the prominent formulas for estimating evaporation is given in Meyer's "Hydrology," pages 188 to 220, but no new data are added. Mr. Meyer's formula is published in the Transactions of the Am. Soc. C. E. for 1915, page 1074.

PRELIMINARY STUDIES BY C. F. MARVIN

Toward the close of the series of papers by Professor Bigelow on the Salton Sea problem, Professor C. F. Marvin, Director of the United States Weather Bureau, presented two papers in the Monthly Weather Review; the first in the issue for February 1909, page 57, under the title "A Proposed New Formula for Evaporation." The second in April 1909, entitled "Methods and Apparatus for the Observation and Study of Evaporation." The first comprised a summary of the physical laws of evaporation (so far as known), and the second described many proposed new instruments for precise measurements of evaporation.

These two papers, if followed up, promised to be the most fruitful of any papers on evaporation in recent years, but nothing appears to have since been done along these lines within the 17 years that have followed.

The analytical treatment of the problem of evaporation by Professor Marvin appeals to the present writer as the most rational, of any that he has seen. Professor Marvin only suggests the form for his equations, without proceeding to give constants or to put the whole in form for practical application.

For measuring the influences of the wind, he suggests that a rational form of function f(v), should provide for a rapid increase in the early stages of change from calm to moderate wind, then decrease rapidly in rate and follow nearly a straight line, until the wind becomes so strong that waves on a broad lake surface begin to form white-caps, after which, the line of increased evaporation for each added mile of wind velocity would increase more rapidly. He says,

> "Nearly all ordinary evaporation in Nature, however, is so dominated by the action of wind, even when gentle, and by convection generally, that the mechanics of the phenomena are very complex and very different from one of pure diffusion.
>
> "Close down to the free water surface we must have a thin layer of air that is heavily charged with water vapor. This indicates that the dense vapor sheet is very thin. We know, however, from our knowledge of viscosity and the flow of fluids, that in spite of ordinary moderate wind action, the thin gaseous sheet immediately next to the water is changed and renewed by the wind only with relative slowness. The further solution of these important details must be deferred until more new data on evaporation are available."

The writer is at loss to know why these admirable new departures in theory and in methods of experiment, which bid so fair to develop excellent data and formulas for estimating evaporation from reservoirs and lakes, have not been followed up by ample observations during the past 17 years.

The total funds needed to be appropriated for equipping a selected number of the present U. S. Weather Bureau stations with the required apparatus, would be extremely small, relatively to the practical importance of the information that could be obtained. Meanwhile a staff in which there are experienced and enthusiastic observers, is already organized in readiness for collecting data under a great variety of climatic conditions all over the United States.

Records by the Nearest U. S. Weather Bureau Standard Land Tank Evaporimeters

The nearest U. S. Weather Bureau Stations, where evaporation is now systematically measured, are from 50 to 100 miles away from the shores of the Great Lakes.

These are located at Ithaca, N. Y.; Albany, N. Y.; Wooster, Ohio; Columbus, Ohio; and Centerville, Minn.

The standard methods of measuring evaporation adopted by the U. S. Weather Bureau in recent years (according to Department "Circular L," Instrument Division, 1915, received November 20, 1925, entitled "Instructions for Installation and Operation of Class A Evaporation Stations"), is an open galvanized iron tank, four feet in diameter and eight inches deep, placed on a wooden platform bedded on the ground, which is kept nearly full and its loss of water measured from day to day with great precision by a micrometer gage, and the water lost, frequently replenished.

A Robinson anemometer is placed close to the tank, one foot above the surface, for recording the daily travel of the wind.

No thermometer is immersed below the surface of the water, but two thermometers, a maximum and a minimum, for measuring the temperature of the air, are exposed within a louvered box shelter, three feet above the ground near the tank. This mean gives very nearly the average air temperature for the 24 hours.

In freezing weather the tank is emptied and observations are suspended.

These shallow land tanks may be expected to give consistent results, by which, differences in evaporation from year to year, at the same locality, and differences in the evaporation in one locality as compared with that at another, can be accurately compared, but certainly **they do not represent the conditions in a natural lake, sufficiently to be accepted as giving an accurate measurement of its evaporation loss.**

Probably, in general, these weather bureau standard land tanks will evaporate at least 33% more water than a standard tank floating in a lake. The shallowness of the water in the tank, and the heating of the sides of the tank, and the capillary attraction of thin film of water up the sides of the heated tank by exposure to the sun, all tend to cause larger evaporation.

The Denver experiments by Mr. Sleight, described on page 433, showed 50% excess.

Records of the total monthly depths evaporated in what are understood to be the five nearest weather bureau standard tanks, for five years, were obtained from the U. S. Weather Bureau, and compared with records from the floating tanks which have been used, but finally were rejected as not applicable to conditions over the Great Lakes for supplying engineering data, although presumably they would not be carried on unless they were believed useful in agricultural experiments.

That results from these shallow land tanks are erratic, is shown by the record for Centerville, Minn., being consistently 25% larger in the same months than the other nearest stations in Ohio and New York.

RECORDS OF WATER TEMPERATURES ON THE GREAT LAKES

The freedom from ice-cover on the Great Lakes presents a condition very different from that found in the reservoirs upon which evaporation has been observed. (See notes on ice, on pages 91 to 96.)

The temperature of the surface water on the Great Lakes promptly follows the temperature of the air down to 32 degrees F., and there it remains until the following spring. Meanwhile, through the winter the temperature of the air at shore stations may fall at times to 10 degrees or to 30 degrees below zero, particularly in the Lake Superior region, **so as to give very much larger evaporation than from an ice-covered reservoir,** or one where the ice is covered by a non-conducting blanket of snow.

According to Dalton's Law, the amount of evaporation continues proportional to (V–v), down within these low temperatures.

Much difficulty has been found in obtaining comprehensive records of surface water temperatures over representative portions of the entire Great Lakes areas. There appear to have been no such continuous systematic and dependable observations upon water temperature as are found for air temperatures in the records of the U. S. Weather Bureau at its many stations around the southern lake harbors.

The following described records have been found and used in preparing isothermal maps of the water temperatures, for each month, from which the mean values were derived for purpose of estimating evaporation by the third and fourth methods, described in the preceding pages.

(1) The U. S. Signal Service Records, furnished by Mr. N. B. Conger. (Referred to in this report as "The Conger Records.")
(2) The Townsend Records.
(3) Sundry Lighthouse and Lightship Records.
(4) Records from Engine Room Logs of certain Lighthouse tenders.
(5) Records at 2-mile crib of the Chicago Water Works.
(6) Records from the Detroit Water Works.
(7) Records from the Duluth Water Works.

A description of these several series of observations follows.

U. S. Signal Service Observations

(1)—About 40 years ago, Mr. Norman B. Conger, inspector of the U. S. Weather Bureau office at Detroit, prepared a compilation of temperatures observed at 2 p. m., continuously from 1874 to 1886, near most of the regular weather bureau stations, which is reproduced in the table below.

(Mr. Conger also, many years ago, co-operated in extensive investigations of water temperatures in mid-lake at surface and at great depths, the records of which were not published and have apparently become buried so deeply in the archives at Washington that the writer has been unable to obtain them. He has been told unofficially that the purpose of these observations on deep water temperatures was to aid in the studies of the fish life in the Great Lakes more than as a basis for weather predictions.)

AVERAGE TEMPERATURE OF SURFACE WATER OF GREAT LAKES

From a Compilation by Norman B. Conger of 13 years Observations, 1874 to 1886, made for the U. S. Signal Service.

	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Duluth, Minn.	(32.0)	(32.0)	(32.5)	(36.0)	(41.1)	53.3	60.3	64.9	57.2	(48.8)	40.0	(34.0)
Marquette, Mich.	(32.2)	(32.0)	(32.4)	(36.0)	(40.8)	(48.4)	(57.4)	(61.1)	(56.9)	49.4	(40.9)	(33.4)
Superior Average	32.1	32.0	32.4	36.0	41.0	50.8	58.0	63.0	57.1	49.1	40.5	33.7
Escanaba, Mich.	(32.0)	(32.0)	(32.3)	(38.1)	(47.0)	59.6	66.0	67.1	(60.5)	52.2	41.5	(32.4)
Milwaukee, Wis.	(32.2)	(32.4)	(33.9)	(40.7)	(49.7)	(55.4)	(62.2)	(65.9)	(60.6)	(50.9)	(41.5)	(33.1)
Chicago, Ill.	(32.7)	(33.1)	(34.5)	(43.4)	(54.6)	(61.9)	(68.0)	(70.8)	65.3	55.8	(42.3)	(33.0)
Grand Haven, Mich.	(32.3)	(32.0)	(34.9)	(48.0)	60.4	70.3	75.4	74.1	66.6	54.6	40.8	(33.6)
Mich.-Huron Aver.	32.3	32.4	33.9	42.5	53.9	61.8	67.9	69.5	63.2	53.4	41.5	33.0
Alpena, Mich.	(32.0)	(32.0)	(32.4)	(41.0)	53.2	64.6	70.3	69.1	(61.7)	(50.3)	(38.2)	(32.4)
Detroit, Mich.	(32.5)	(32.2)	(33.6)	(42.1)	54.0	(64.2)	(71.5)	71.9	66.4	55.5	(42.5)	(33.3)
Average	32.2	32.1	33.0	41.5	53.6	64.4	70.9	70.5	64.0	52.9	40.3	32.8
Toledo, Ohio	(33.0)	(32.4)	(36.6)	(50.2)	61.2	73.5	78.2	76.1	69.5	(58.1)	(42.9)	(33.7)
Sandusky, Ohio	(32.8)	(32.2)	(35.0)	(46.9)	(60.3)	(69.9)	(75.6)	74.0	67.3	56.1	41.9	(33.1)
Cleveland, Ohio	(32.9)	(32.4)	(33.3)	(44.5)	(55.6)	(66.5)	(74.1)	(73.5)	(68.4)	(58.2)	45.8	(33.7)
Buffalo, N. Y.	(32.4)	(32.0)	(33.6)	(42.0)	49.7	(64.2)	72.8	72.7	67.9	(56.2)	(42.5)	(33.8)
L. Erie Average	32.8	32.2	34.6	45.9	57.2	68 5	75.2	74.1	68.3	57.1	43.3	33.6

Parentheses indicate that some of the 13 values averaged were interpolated. Interpolated values are relatively few except in winter months.

Nearly all values for December, January, February and March were interpolated.

Data Pertaining to Depth and Character of Bottom at Localities Where the Above Temperatures Were Measured.

Station	Depth of Water	Place in Harbor Where Temp. was Obs'd
Duluth, Minn.	12 ft.	At the foot of Third Avenue, East, at the railroad freight sheds.
Marquette, Mich.	11 ft.	At foot of Spring St.
Escanaba, Mich.	17 ft.	At the Goodrich Docks, foot of Tilden Ave.
Milwaukee, Wis.	8 ft.	At a pier in Milwaukee Bay at foot of Huron St. Location changed to foot of Wisconsin St., in June, 1883. No change in depth of water.
Chicago, Ill.	8 ft.	From a stone pier extending into the Lake; bottom rocky.
Grand Haven, Mich.	19 ft.	At foot of Franklin St., Grand River.
Alpena, Mich.	12 ft.	At foot of Dock St., and the Drawbridge; bottom sandy.
Detroit, Mich.	24 ft.	From southwest corner of coal wharf, foot of Griswold Street.
Toledo, Ohio	12 ft.	At. W. T. Walker's Dock, foot of Madison St., until March, 1884, then at Howell's wharf foot of Walnut St. bottom muddy.
Sandusky, Ohio	11 ft.	At foot of Columbus Ave., from Hudson's Dock.
Cleveland, Ohio	14 ft.	From Ohio and Pennsylvania Company's coal wharf extending into Lake Erie.
Buffalo, N. Y.	10 ft.	From a dock at the mouth of the river; bottom soft.
Mackinaw City, Mich.	11 ft.	At the head of the "Old" Dock to August 1, 1883, at the "Citizens" Dock from then on; depth of water at last named dock one foot less than at "Old" Dock.

A small adjustment is required to obtain the values of monthly mean daily surface temperatures from these maximum daily temperatures presented by Mr. Conger. The average of observations for 10 years past at the two-mile crib of the Chicago water works appears to give a proper basis for this adjustment.

Investigation of Lake Temperatures and Currents by Col. C. McD. Townsend, U. S. Corps of Engineers.

(2)—The next most complete study of water temperatures in the Great Lakes that the writer has found, is contained in Appendix C., House Document 762, 63rd Congress, 2nd Session; which is a part of a report on a waterway from Lockport, Ill., to the mouth of the Illinois River, dated August 13, 1913. This report on water temperatures, while admirably complete for its special purpose, and giving more data on certain features than found elsewhere, was not directed toward studies on evaporation and therefore misses some points that now are of special interest. Its subject was "Effect upon the Climate of the Lake States by a change in the Natural Current of Lake Michigan."

The report states:

> "While variations in the levels of the Great Lakes have been carefully studied for a long while on account of their influence on harbors and connecting waters, it is only during recent years that data has been collected upon their temperature and currents. The information thus obtained is not only incomplete, but the conclusions derived therefrom by different observers are frequently contradicted. The Board therefore considered it necessary to make a series of independent investigations."

The temperature of Lake Michigan, off Frankfort, was determined at different depths down to 600 feet. Similar sets of observations were taken in Lake Huron, off Harbor Beach; in Lake Erie, off Long Point; in the Straits of Mackinac and in the Detroit River. These deep-water temperatures were found as set forth in the following table.

In general, little difference in temperature was found in the top 20 feet. Below 100 feet in the deep lake, temperatures were found constantly at about 44° F. to 48° F.; except in Lake Erie, which gave slightly higher values. The lake outlets showed more nearly average values.

Water Temperatures at Great Depths

Lake Michigan off Frankfort Aug. 11, 1911		Straits of Mackinac Aug. 9, 1911		Lake Huron off Harbor Beach Aug. 5, 1911		Detroit River Aug. 25, 1911		Lake Erie off Long Point July 14, 1911	
Depth	Temperature	Depth	Temperature	Depth	Temperature	Depth	Temperature	Depth	Temperature
Feet	°F.	Feet	°F.	Feet	°F.	Feet	°F.	Feet	°F.
Surface	64½	Surface	64	Surface	68	Surface	68½	Surface	72
50	58	20	64	20	64½	20	68½	20	72
100	47	40	62	40	60	40	68½	40	62
150	46	60	57	60	55	....	....	60	48
200	46	80	56	80	54	....	....	80	46
250	46	100	55	100	46½	....	....	100	45
300	45	120	55	120	45½	....	....	120	53
400	48	140	54½	140	44½	....	....	140	52
500	47	160	53	150	44	....	....	160	51
600	48	180	53	....	....	....	....	180	54
....	....	200	53	....	....	....	....	....	....

These temperatures were measured with apparatus loaned by Mr. Conger, comprising an accurate glass and mercury thermometer, set in a brass tube about an inch in diameter and a foot in length, provided at top and bottom with check valves which admitted a current of water while being lowered, but closed when apparatus was raised.

The precision of this type of apparatus is less certain, when slowly raised through warmer water, than deep temperature measurements by the electrical "Thermophone," used by Whipple on certain lakes and reservoirs in Massachusetts.

These midsummer temperatures at depths below 100 feet are so much above the temperature of maximum density, 39.2°, as to indicate that **the sweep and force of the wind over these broad areas, affects temperatures by interchange or mixture with surface water, to greater depths than generally supposed.**

Lake Superior was not within the scope of this series of observations by Colonel Townsend.

The temperature of the surface water and of the air, also the direction of currents in Lake Michigan, were observed daily during the summer months of 1911 at the lighthouses at Chicago, Milwaukee, Grand Haven, and White Shoals; and in Lake Huron surface water temperatures were observed at Spectacle Reef, Harbor Beach and at the lightship on Poe Reef, and that off Fort Gratiot.

Daily observations also were made of the surface temperatures of the Chicago and St. Marys Rivers and the Straits of Mackinac. The hour of observation is not stated, but it is inferred that ordinarily these observations were at noon.

The average results for each month, of the light-keeper's daily observations, are given in the following table.

Comparison of Air and Surface Water Temperatures in Great Lakes Observed by Light Keepers Each Day Probably at Noon in Connection with Colonel Townsend's Investigation

LAKE MICHIGAN

Year	White Shoal Light *		Milwaukee Pier-head Light		Grand Haven Light		Chicago Harbor Light		Chicago River Rush St. Bridge	
1911	Water	Excess Air Over Water	Water	Excess Air Over Water	Water	Excess Air Over Water	Water	Excess Air Over Water	Water	Excess Air Over Water
June (20 days)	56.3	5.7	62.2	12.4	63.6	9.1	66.1	7.5	55.2	23.5
July....................	63.3	4.4	64.1	14.0	71.8	3.9	68.3	7.8	64.3	10.9
August	65.9	2.2	62.2	12.5	65.2	7.1	67.8	7.5	68.8	8.7
September..........	60.3	—1.5	62.9	6.8	57.3	5.5	67.3	0.8	66.1	6.3

LAKE HURON

Year	Mackinac Island Vessel *		Poe Reef Light Vessel *		Spectacle Reef *		Harbor Beach Light		Lightship No. 61 off Ft. Gratiot *	
1911	Water	Excess Air Over Water	Water	Excess Air Over Water	Water	Excess Air Over Water	Water	Excess Air Over Water	Water	Excess Air Over Water
June (20 days)	56.0	6.6	56.1	7.1	53.7	7.0 (18 days)	62.9	6.6	61.6	11.7
July....................	61.1 (22 days)	9.7	62.8	8.1	59.6	7.2	66.1	10.4	68.8	8.5
August	....	....	63.2	6.6	61.3	4.8	....	....	67.6	10.0
September..........	....	....	56.6	5.7	57.8	1.2	62.2	3.3	65.2	6.0

*White Shoal Light is at northeast end of Lake Michigan.
Mackinac Island is in Straits of Mackinac or in the extreme northern part of the Michigan-Huron system.
Poe Reef and Spectacle Reef are at northwest end of Lake Huron, near Mackinac Island.
Lightship No. 61 off Fort Gratiot is at mouth of St. Clair River.

Distances from south to north, explain many of these differences in the surface temperature of the lake at different localities, when viewed in connection with isothermal maps.

Many other records of both air and water temperatures are given in Colonel Townsend's report. The water surface temperatures were measured at 8 a. m. and 4 p. m. The table above gives monthly mean values from daily observation.

During July and August, the Steamer Hancock circumnavigated Lakes Erie, Huron and Michigan, and surface temperatures were taken meanwhile at intervals of one hour, while cruising, which are recorded on a chart of the cruise of which a copy is printed with Colonel Townsend's report.

For the purposes of the present report all of these values for water temperatures, presented above and in the following tables, were considered and roughly averaged, while preparing the maps of water isotherms used in obtaining average values. These maps have not been reproduced in this report.

Mean Surface Water Temperatures of the Great Lakes

(Observed by Light Keepers from 1905 to 1908)

Month	LAKE SUPERIOR: Devil's Island Lighthouse at West End of Lake Among Apostle Islands		Passage Island at North-East End of Isle Royal 40 Miles East of Port Arthur		Stannard Rock Lighthouse About 45 miles North of Marquette, Michigan		LAKE HURON: Spectacle Reef Lightship in Straits of Mackinac Northwest End of Lake Huron		Charity Island Lighthouse in Saginaw Bay		Lake Huron Light Vessel No. 61 off Fort Gratiot at Mouth of St. Clair River	
	1905	1906	1905	1906	1905	1906	1905	1906	1905	1906	1905	1906
Jan.	......	......	......	......	......	......	......	......	......	......	......	......
Feb.	......	......	......	......	......	......	......	......	......	......	......	......
March	......	......	......	......	......	......	......	......	......	......	......	......
April	36.1	36.2	33.0	35.3	34.4	34.9	34.8	35.0	48.4	46.4	38.3	39.8
May	40.1	39.4	36.4	37.1	35.8	36.3	37.0	38.3	54.6	54.6	45.4	46.6
June	47.2	46.3	39.7	39.8	38.3	38.3	47.6	51.6	67.1	67.5	59.8	58.8
July	56.4	60.6	44.4	44.9	42.2	47.6	59.5	64.4	72.4	73.1	66.1	68.5
Aug.	61.3	63.0	54.8	55.9	51.4	54.1	65.0	66.7	72.7	75.2	67.7	72.5
Sept.	56.4	59.0	51.6	52.9	50.3	53.0	62.7	61.7	67.1	70.0	65.9	70.0
Oct.	50.0	51.4	47.5	46.5	48.0	47.1	50.3	49.7	53.3	55.3	58.9	57.3
Nov.	42.2	41.5	40.5	39.4	41.8	42.2	41.3	42.6	41.9	42.6	46.5	45.7
Dec.	38.3	36.7	37.1	35.8	......	......	40.0	38.4	36.0	......	39.4	37.3

Month	LAKE MICHIGAN: Lansing Shoal Lighthouse North of Beaver Island, North End of Lake Michigan		Eleven-Foot Shoal Lighthouse North End of Green Bay		Milwaukee Breakwater West Side of Lake Michigan		Grand Haven Lighthouse East Side of Lake Michigan		LAKE ONTARIO: Charlotte Lighthouse in Charlotte Harbor, South Side of Lake Ontario Near Rochester		Galloo Island Lighthouse Near East Extreme End of Lake Ontario	
	1905	1906	1905	1906	1905	1906	1905	1906	1905	1906	1905	1906
Jan.	......	......	......	......	......	32.8	......	......	32.3	......	......	......
Feb.	......	......	......	......	......	32.5	......	......	32.3	......	......	......
March	......	......	......	......	34.2	33.4	......	33.8	38.5	34.6	......	......
April	......	36.8	36.0	38.0	40.1	40.7	42.8	43.8	42.3	42.9	37.6	40.2
May	39.6	40.8	41.8	44.3	46.4	47.4	51.1	51.5	48.5	50.3	45.6	49.3
June	50.1	54.3	53.9	56.1	53.9	53.1	57.9	59.0	59.0	58.5	56.4	60.2
July	59.5	65.5	62.5	66.9	61.4	61.9	62.7	64.3	64.5	57.2	66.5	70.3
Aug.	65.3	66.6	66.9	69.7	67.0	68.5	67.4	70.5	64.9	61.5	68.7	72.9
Sept.	62.2	62.7	62.8	63.5	56.8	58.6	65.5	64.6	62.6	67.2	65.4	65.4
Oct.	55.3	52.9	55.6	54.5	45.0	53.3	55.8	51.6	55.3	54.0	58.2	54.3
Nov.	44.3	43.6	43.8	44.1	39.6	42.7	41.8	44.2	40.0	42.3	45.8	41.1
Dec.	......	37.5	38.0	36.9	34.2	36.4	34.0	33.9	33.9	33.8	37.6	32.0

LAKE ST. CLAIR AND LAKE ERIE

Month	Grosse Point Light Vessel Near Entrance to Detroit River		Toledo Harbor Light Vessel at Entrance to Toledo Harbor			Southeast Shoal Lightship off Point Pelee East of Pelee Island Westerly End of Lake		Horseshoe Reef at Mouth of Niagara River at End of North Breakwater			
	1905	1906	1905	1906	1907	1905	1906	1905	1906	1907	1908
Jan.	......	......	32.0	......	32.3	....	....	......	......	......	......
Feb.	......	......	32.0	......	32.0	......	......	......	......	......	......
Mar.	......	......	......	......	36.7	......	......	......	......	......	......
April	41.0	42.2	43.7	43.7	40.9	......	41.6	32.0	34.9	......	33.6
May	51.5	50.9	57.5	57.0	50.6	......	51.2	45.0	46.9	......	45.7
June	62.4	62.5	69.9	66.9	63.3	70.3	65.0	60.5	59.0	67.3	65.1
July	68.9	70.5	74.4	75.0	73.0	73.5	72.3	69.6	69.4	69.1	71.3
Aug.	70.6	74.2	73.2	77.4	72.1	73.4	76.2	69.8	73.4	69.8	70.9
Sept.	66.1	69.7	68.2	72.4	67.8	68.7	72.2	66.8	69.5	66.8	66.5
Oct.	56.5	55.4	56.8	53.4	53.3	60.1	58.2	59.2	59.1	55.9	58.8
Nov.	42.2	43.4	40.3	43.2	41.7	43.4	46.8	45.2	46.3	45.5	45.4
Dec.	35.9	34.6	33.6	33.9	34.1	35.6	38.4	38.3	35.9	36.9	37.7

Colonel Townsend states his conclusions regarding temperature, drawn from these observations described above, as follows:

"During the months of January and February the surface temperatures of all the lakes fall to about 32 degrees and then gradually rise to a maximum in July and August, which varies from year to year.

This maximum is affected:

(1) By the latitude of the station.
In Lake Michigan, at Chicago (near the southern end of the lake), the maximum monthly mean during the period of observation was............68.3° F.
At White Shoal Light (near the extreme northern end)....................65.9° F.
At the southern end of Lake Huron, at Light vessel No. 61, off Fort Gratiot.. 68.8° F.
At Poe Reef lightship (at its extreme northern end)..........................63.2° F.
Thus the midsummer temperature at the northern end was 2.4° lower in Michigan, and 5.6° lower in Huron than near the southern end of the same lake.

(2) By the depth of the water in the vicinity, water being cooler as the depth increases. The observations of the Lake Survey show that the maximum monthly mean temperature of surface water in Lake Erie at Toledo was..77.4° F.
At Horshoe Reef, off Buffalo...73.4° F.

In Lake Huron, at Charity Island, Saginaw Bay..................................75.2° F.
At Light Vessel No. 61, off Fort Gratiot...72.5° F.
Depths of lake at these stations being 2 to 12 ft. and 20 to 50 ft.

In Lake Michigan, Eleven Foot Shoal, at north end of Green Bay......69.7° F.
Lansing Shoal..66.6° F.
The depths of lake near at hand being 4 to 24 ft. and 17 to 60 ft.

(3) By the direction of the prevailing winds.
At Milwaukee the mean temperature during the month of July, 1911, was...64.1° F.
with the prevailing winds from the west.
At Grand Haven, on the opposite side of the lake...............................71.8° F.
or 5.7° higher at Grand Haven than at Milwaukee.
In September when the winds have a more easterly component, conditions were reversed, the mean temperature of the water
At Grand Haven was...57.3° F.
And at Milwaukee..62.9° F.
or 5.6° higher at Milwaukee than at Grand Haven.

"At any given locality surface temperatures are very variable, changes as great as 10 degrees being liable to occur in summer, within a few hours.

"At any locality near the shore there **is a marked tendency for the surface water to be warmer, when the wind is blowing on shore** than when blowing from the land."

"This is particularly noticeable in the log of the Steamer Hancock for August 21, 22 and 23. In the afternoon of August 21, before entering the harbor of Bruce Mines, with the wind from the southeast, the surface temperature of the water in the north channel was 64° F. In the morning on leaving the harbor a temperature of 53° F. was observed (or 11° less than on previous afternoon), the wind then blowing from the northwest. As the vessel crossed the channel and approached Cockburn Island the water gradually acquired a temperature of 64 degrees. After passing through Mississauga Straits it suddenly fell to 55 degrees, and then gradually rose to 65 degrees off Southampton, on the Canadian shore of Lake Huron.

"The mean surface temperature of the water flowing through the Straits of Mackinac was slightly less than at the nearest lighthouses in Lake Michigan and Lake Huron, being during the period of observation at that locality 59.5 degrees at White Shoal Light, 58.6 degrees at Mackinac Island, and 62.1 degrees at Poe Reef Light.

"The mean temperature of the Chicago River during the periods of the observations averaged 6 degrees less than the surface temperatures of the lake at the entrance to the river (doubtless due to the proportion of deep water drawn in).

"The surface temperature of the water of St. Marys River increased on an average 2 degrees during its passage from Sault Ste. Marie to Sailors Encampment, a distance of 18 miles, and at that locality was about 2 degrees warmer than the surface waters at Spectacle Reef, Lake Huron."

Colonel Townsend also says:

"In Lake Superior at great depths the temperature appears to remain at 39 degrees F. the entire year. In Lakes Michigan and Huron at depths greater than 100 feet, the water remains below 50 degrees during the warmest months. In the rivers forming the outlets to the lakes, due to rapid current and consequent mixing of the waters, the observations at Detroit show that there is little difference in temperature between the water flowing on the surface and that on the bottom of the river. In the Straits of Mackinac at a depth of 100 feet the water was about 10 degrees warmer than at corresponding depths in Lake Michigan and Lake Huron.

"At the time the observations were made, the temperature of the air was warmest at Milwaukee and coldest at White Shoal Light, the average air temperature at Milwaukee being 1 degree warmer than at Chicago, 3.4 degrees warmer than at Grand Haven, and 10.2 degrees warmer than at White Shoal Light. But it is to be noted that White Shoal Light is at considerable distance from land, so that its air temperatures are affected by lake influences whatever the direction of the wind."

Regarding the wind, Colonel Townsend said:

"The most noticeable characteristic of the winds is their extreme variability both in force and direction during the period of observations. There is, however, a decidedly easterly component to the wind at Milwaukee and Chicago, and a westerly component at Grand Haven and White Shoal Light."

In other words, the summer wind is mostly from off the water on to the land, so that **observations by day at Weather Bureau stations would get temperature and humidity readings representative of temperature and humidity affecting evaporation in mid-lake.**

This is particularly apparent when the wind is light, tho some diversion is observed even in strong wind and is due to the influence of the lake on the air passing over. The observations were taken at noon when the sun's rays are producing their maximum effect. The soil having much less capacity to absorb heat than the water, the air over the land becomes warmer and lighter than the air over the lake and there is a current from the latter to the former to restore equilibrium. After sunset, in summer, a return flow from the land is observed.

Also the elevation of the water is raised by the wind on the leeward side of the lake and lowered on the windward side, and this disturbance of the equilibrium **causes a return flow below the surface,** but probably not extending to the lake bottom. The frequent change in the direction of the wind tends to continually change the location at which this sub-surface flow occurs and causes more or less mixing of the waters.

Chicago Records of Water Temperature

(3)—Water temperatures and air temperatures have been systematically measured, for many years past, daily at the "Two-Mile Intake Crib" of the Chicago water works. At 7 a. m., 2 p. m., and 7 p. m. the air temperature is measured by an ordinary mercurial thermometer placed on the outside of the crib, with a northeast exposure. The crib is located about 1.77 miles from shore, in 29 feet average depth of water. Similar records are kept at all of the cribs.

A copy on reduced scale of two of these Chicago yearly graphs of records of daily means is given on page 453. The water temperature is measured inside the crib, and represents the average temperature of water from all depths, from 2 feet below the surface to 20 feet below. It is stated that other observations have shown that the surface temperature of water outside the crib does not ordinarily differ materially from that as measured inside the crib.

Among other facts of interest, this graph serves to bring out clearly the wide variations of temperature from day to day, between the daily means and monthly means.

MONTHLY MEAN AIR TEMPERATURES OBSERVED AT CHICAGO TWO-MILE CRIB

	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Aver. An'ual
1915	25	35	36	58	55	65	70	67	67	57	45	30	50.8
1916	29	27	34	48	59	63	79	77	66	54	44	27	50.6
1917	24	22	37	45	52	64	72	71	64	52	44	24	47.6
1918	14	28	42	47	64	68	73	77	60	59	44	38	51.2
1919	30	30	39	49	56	72	78	74	70	59	41	22	51.7
1920	20	27	41	44	55	69	71	72	70	63	42	34	50.7
1921	31	32	45	53	62	74	82	73	69	55	41	32	54.1
1922	26	28	40	49	64	72	74	73	69	56	44	29	52.0
1923	30	23	34	47	54	70	74	71	65	54	45	40	50.6
1924	20	29	35	49	56	64	70	71	61	58	42	22	48.1
Average	24.9	28.1	38.3	48.9	57.7	68.1	74.3	72.6	66.1	56.7	43.2	29.8	50.7

MONTHLY MEAN WATER TEMPERATURES AT CHICAGO TWO-MILE CRIB

	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Aver. An'ual
1915	32	33	36	45	52	56	64	67	64	56	45	34	48.7
1916	32	32	33	39	51	57	67	71	61	52	43	34	47.7
1917	32	32	34	40	46	52	62	68	62	50	41	33	46.0
1918	32	32	35	40	49	59	63	70	62	56	46	37	48.4
1919	32	32	34	42	49	57	68	70	67	58	45	32	48.8
1920	32	32	34	39	46	56	62	66	66	59	44	36	47.7
1921	32	32	36	44	51	62	78	69	63	52	43	36	49.8
1922	32	32	34	42	46	62	66	70	66	56	48	34	49.0
1923	32	32	33	38	47	55	66	70	64	56	45	38	48.0
1924	32	32	32	40	49	55	64	63	58	56	47	33	46.7
Average	32	32.1	34.1	40.9	48.6	57.1	66.0	68.4	63.3	55.1	44.7	34.7	48.1
Excess of Air Over Water	−7.1	−4.0	4.2	8.0	9.1	11.0	8.3	4.2	2.8	1.6	−1.5	−4.9	

(The writer has found by recent enquiry that the wind velocities recorded daily at the Chicago Intake Cribs for a long time past have not been measured by any instrument but represent the guess or judgment of the keeper.

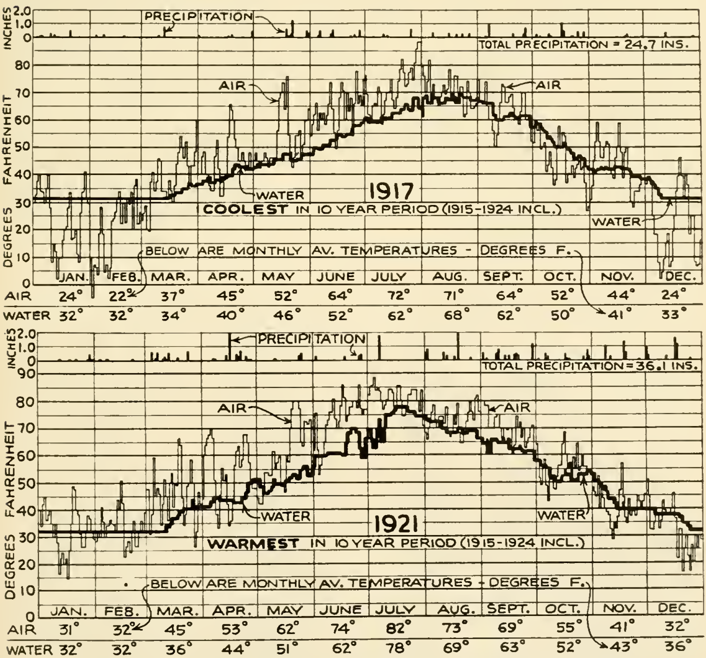
The temperatures seem to have been carefully measured.)

Water Temperatures in Lake Michigan at Chicago Intake Crib

The diagrams below show two examples of observations made continuously during the past ten years at the intake crib of the Chicago water works, located about two miles from shore, show an average mean monthly temperature of water in May, June, July and August averaging about 7 degrees Fahrenheit smaller than the mean temperature of the adjacent air.

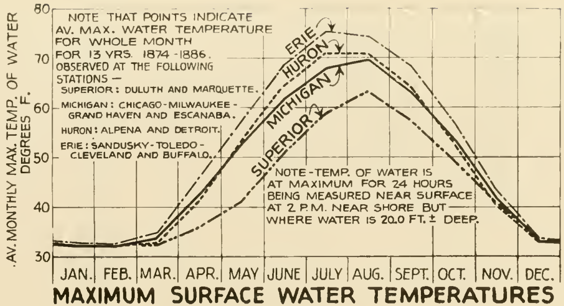
The depth of lake in the vicinity of the crib is only about 25 feet, but currents from the broad, deep lake doubtless sweep past the crib, and influence this temperature.

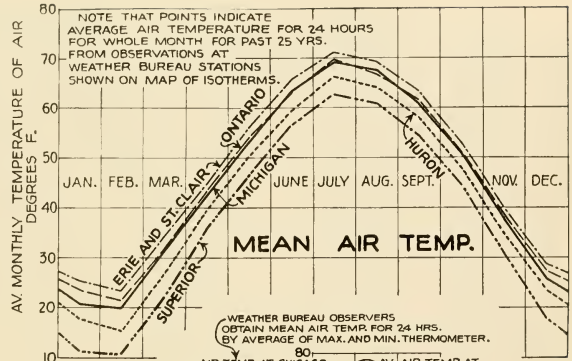
These water temperatures measured within the crib represent the average temperature as taken in through ports from two feet to about 20 feet below the surface, and doubtless are but very slightly less than the mean surface water temperatures for the 24 hours, outside the crib.

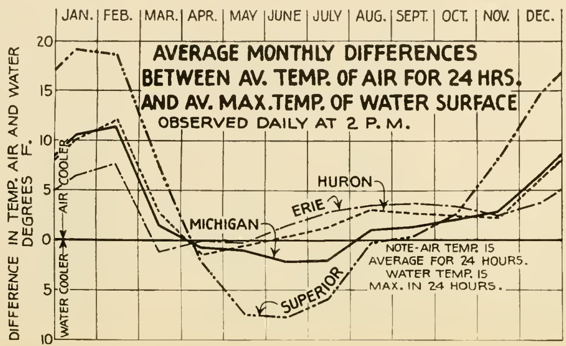


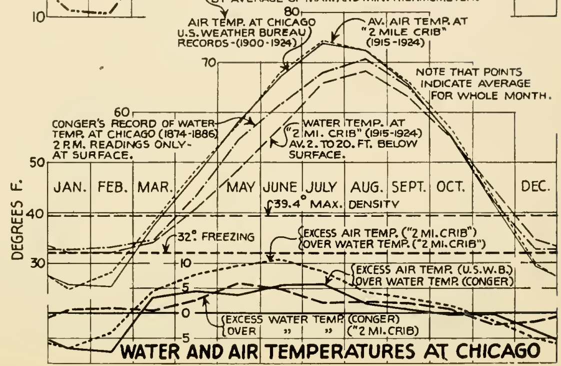
DAILY AIR AND WATER TEMPERATURES
AT 2-MILE INTAKE CRIB OF CHICAGO WATER WORKS

The diagram in the lower right hand corner of the next page shows that these water temperatures at the Chicago crib for May, June, July and August **average about four degrees smaller than the maximum daily surface water temperature measured at 2 p. m. near the shore.**


MAXIMUM SURFACE WATER TEMPERATURES
NOTE THAT POINTS INDICATE AV. MAX. WATER TEMPERATURE FOR WHOLE MONTH FOR 13 YRS. 1874-1886. OBSERVED AT THE FOLLOWING STATIONS —
SUPERIOR: DULUTH AND MARQUETTE.
MICHIGAN: CHICAGO-MILWAUKEE-GRAND HAVEN AND ESCANABA.
HURON: ALPENA AND DETROIT.
ERIE: SANDUSKY-TOLEDO-CLEVELAND AND BUFFALO.
NOTE-TEMP. OF WATER IS AT MAXIMUM FOR 24 HOURS BEING MEASURED NEAR SURFACE AT 2 P.M. NEAR SHORE BUT WHERE WATER IS 20.0 FT.± DEEP.
ERIE
HURON
MICHIGAN
SUPERIOR
AV. MONTHLY MAX. TEMP. OF WATER DEGREES F.
80
70
60
50
40
30
JAN. FEB. MAR. APR. MAY JUNE JULY AUG. SEPT. OCT. NOV. DEC.


MEAN AIR TEMP.
NOTE THAT POINTS INDICATE AVERAGE AIR TEMPERATURE FOR 24 HOURS FOR WHOLE MONTH FOR PAST 25 YRS. FROM OBSERVATIONS AT WEATHER BUREAU STATIONS SHOWN ON MAP OF ISOTHERMS.
ONTARIO
ERIE AND ST. CLAIR
MICHIGAN
SUPERIOR
HURON
AV. MONTHLY TEMPERATURE OF AIR DEGREES F.
80
70
60
50
40
30
20
10
JAN. FEB. MAR. JUNE JULY AUG. SEPT. NOV. DEC.


AVERAGE MONTHLY DIFFERENCES BETWEEN AV. TEMP. OF AIR FOR 24 HRS. AND AV. MAX. TEMP. OF WATER SURFACE OBSERVED DAILY AT 2 P.M.
HURON
ERIE
MICHIGAN
SUPERIOR
NOTE-AIR TEMP. IS AVERAGE FOR 24 HOURS. WATER TEMP. IS MAX. IN 24 HOURS.
DIFFERENCE IN TEMP. AIR AND WATER DEGREES F.
AIR COOLER
WATER COOLER
20
15
10
5
0
5
10
JAN. FEB. MAR. APR. MAY JUNE JULY AUG. SEPT. OCT. NOV. DEC.


WATER AND AIR TEMPERATURES AT CHICAGO
WEATHER BUREAU OBSERVERS OBTAIN MEAN AIR TEMP. FOR 24 HRS. BY AVERAGE OF MAX. AND MIN. THERMOMETER.
AIR TEMP. AT CHICAGO U.S. WEATHER BUREAU RECORDS-(1900-1924)
AV. AIR TEMP. AT "2 MILE CRIB" (1915-1924)
NOTE THAT POINTS INDICATE AVERAGE FOR WHOLE MONTH.
CONGER'S RECORD OF WATER TEMP. AT CHICAGO (1874-1886) 2 P.M. READINGS ONLY-AT SURFACE.
WATER TEMP. AT "2 MI. CRIB" (1915-1924) AV. 2. TO 20. FT. BELOW SURFACE.
39.4° MAX. DENSITY
32° FREEZING
EXCESS AIR TEMP. ("2 MI. CRIB") OVER WATER TEMP. ("2 MI. CRIB")
EXCESS AIR TEMP. (U.S.W.B.) OVER WATER TEMP. (CONGER)
EXCESS WATER TEMP. (CONGER) OVER " " ("2 MI. CRIB")
DEGREES F.
80
70
60
50
40
30
10
5
0
5
JAN. FEB. MAR. MAY JUNE JULY AUG. SEPT. OCT. DEC.

The temperature of water at the surface has been observed and recorded regularly by some of the lighthouse keepers on the Great Lakes in various years.

In water supply paper No. 520, of the U. S. Geological Survey for 1923–1924, are given monthly means of surface water temperatures and air temperatures at Cleveland for 1923, at Detroit for 1918 to 1921 inclusive, and at Toledo for 1921 to 1923 inclusive, at water works and weather bureau stations.

Records of water temperatures from water works intakes must be used with caution as a basis for estimating evaporation, until precise information is had of the conditions of measurement and until it is certain they represent normal lake-surface temperatures. Some anomalous results have been published.

Recent inquiry at the Lake Survey office at Detroit failed to discover any systematic records of water temperatures, but it was suggested that good data might be obtained by a study of the engine room logs of lake steamers, which regularly record the temperature of water supplied to the condensers.

Effect of Spring and Fall Overturn on Lake Temperatures

The relations of water temperatures near the surface to those at great depths, and the change that occurs every spring and fall in shallow reservoirs, has been excellently stated by Mr. Allen Hazen (page 14, "Clean Water and How to Get It"), as follows:

"In our climate, when a reservoir or lake is more than from twenty to forty feet deep, the upper part of the water is usually in circulation under the influence of the wind, and the lower part remains stagnant. There is little or no mixing between the surface water and the bottom water except for two short periods each year, one in the spring and one in the fall. These periods of circulation to the bottom are known to water works men respectively as the spring turnover and the fall turnover.

"At the time of the spring turnover all the water mixes from top to bottom and has a temperature approximately at that at which water has its greatest density, namely, 39 degrees Farenheit. Afterwards the sun warms the surface water above this temperature. This makes it lighter, and then it will not go down again to mix with the colder and heavier water below, but remains at the surface.

"The wind stirs it up for a certain depth. This depth is about 20 feet in small reservoirs, and about 40 feet in the Great Lakes. In this surface layer the temperature may rise in mid-summer at the surface to 75 degrees or 80 degrees or more.

"Below, the water is cooler, and some distance down it rapidly falls to the temperature of the whole mass of the bottom water. And this bottom layer to within 20 or 40 feet of the surface, depending upon the size of the reservoir, remains quiet and stagnant and unmixed with the surface water from spring until fall. Its temperature gradually and slowly increases, but it is always cool and still.

"In the fall the temperature of the top water falls, until it approaches that of the bottom water. As the difference is less the wind action extends deeper, until, all at once, often when the wind is blowing, all the water in the reservoir turns over and mixes from top to bottom. The mixing continues for a few weeks, until the temperature of the surface water falls below the point of maximum density. Then the cold water commences to accumulate near the top."

Influence of Great Depth of Lakes on Surface Temperatures

Over these Great Lakes, where depth is from 500 to 1,000 feet, it is plain that some of the important conditions controlling evaporation are different from those which controlled evaporation at the small floating tanks in shallow reservoirs at which our data were measured, which gave the total depth of evaporation in each month of the year corresponding to the temperature.

It is important to consider the relation of water temperatures at great depth to those at the surface, while studying conditions affecting evaporation from the Great Lakes.

In the deeper portions of the Great Lakes, the water remains at about the temperature of maximum density, throughout the year; and severe winds appear to stir these Great Lakes to greater depths than indicated by the preceding quotation from Mr. Hazen.

Lake Superior presents conditions for which we have no precedent, and, have but little definite information.

Mr. Norman B. Conger, meteorologist of the U. S. Weather Bureau at Detroit, co-operated in making many careful observations on mid-lake temperatures, years ago, and reports finding, occasionally, surface temperatures of **water at 42° F. in midsummer on Lake Superior,** throughout a day's cruising.

In a broad, shallow reservoir, having depth not exceeding 20 feet, open to the prevailing winds, and **particularly in a small tank floating in such a reservoir,** according to treatises on physics (for example see Barnes, on Ice Formation, page 12), about 90 per cent of the sun's rays are absorbed in the upper layers, while 10 per cent may reach the bottom; so that, with the aid of the wind in causing vertical circulation, the mean surface temperature of the water for 24 hours probably seldom averages for any long period more than from one to three degrees Fahrenheit different from the mean temperature of the mass of water from top to bottom, except in the winter months, or when the surface water temperature is below 39 degrees F.

On the contrary, in a reservoir more than 100 feet deep, the surface temperature may differ greatly from that of the deep water, during all but one or two months of the year, and the great mass of water, about the temperature of maximum density (39.2 degrees F.), in the depths of the lake, may hold the surface temperature of the water considerably below that of the air in the months of maximum evaporation, **and cool water from the depths may be brought to the surface irregularly, by currents set in motion by wind or seiche.**

Much greater difference between mean monthly temperatures of water and air was noted in the floating tank at the Lake of the Woods than was observed at Boston and Rochester. Probably this was due to the greater depth of the lake,—about 100 feet as compared with 20 feet,—and to the presence during the summer of water at a much lower temperature near the bottom of the lake, some of which mixed with the surface water in process of discharging past the location of the gage.

The foregoing notes will serve to show the difficulty of obtaining accurate records of the surface water temperatures of the Great Lakes. They also show that an earnest search has been made, and a careful compilation and averaging of the best that can be found.

Accurate knowledge of the surface water temperature is of greater importance than any other one line of data (except dew-point temperature of air), for correctly estimating the evaporation, month by month, that has occurred from the Great Lakes.

Various other diagrams and tables used in obtaining the mean values of surface water temperatures in the several lakes have not been reproduced in the present record. Enough have been given to show the character of the data that have been used and the care taken to confirm the various items.

The reason for setting forth this matter of air temperatures and water temperatures here at such great length is;

(1) To find explanation for the extraordinary conditions of negative yield of Lake Superior in winter, also to find the cause of the apparent small water yield from Lake Erie and to make certain whether or not this can be due to errors in gaugings.

(2) To find further cause beyond small rainfall, for recent lowering of the Great Lakes.

(3) To emphasize its importance in studying the variable loss by evaporation from all of these lakes, and as a basis for urging that systematic accurate observations on evaporation from tanks at opposite sides of such lakes should be begun and the record published in the *Monthly Weather Review*, and in reports of the Lake Survey, or wherever they will be available as data.

Such tanks should be on the most exposed locations available, and of generous size, not less than 6 feet in diameter by 5 feet deep. Better data can be secured on rigidly supported tanks than on floating tanks. Temperature should be maintained the same as at the lake surface by any convenient device, and the water surface in the tank kept open in winter, by warning barely enough to keep an ice sheet from forming over more than 1 per cent. of the top area while holding the water temperature at 32°F. Mechanical means for stirring should be provided.

Experiments with a sheet metal wind deflector in the form of a frustrum of an inverted cone, with base of about the same diameter as the tank, arranged to cause air to circulate in the pocket below the rim, would be instructive; and if a mechanical agitator can be introduced to simulate wave action this also could add useful information.

Mid-lake water temperatures can be obtained by arrangement with steamship engine room chiefs, who regularly observe and record it, as affecting performance of condensers, as part of the engine-room log, but it will be necessary to supply them with certified thermometers. Shipmasters can aid in records of fog.

The four items of data of greatest importance for estimating evaporation from these vast water surfaces are:

(1) Temperature of water, within 10 feet of surface.

(2) Dew-point temperature of air **over lake.**

(3) Force of wind in miles per hour **near the level of the lake.**

(4) Continuous observations on opposite sides of lakes, with record of force and direction of wind (for estimating influence of vapor blanket).

(5) Records of location and duration of fog and haze, daily.

The data now available upon each of these five principal controlling features are scant and unsatisfactory.

It is to be hoped that the U. S. Lake Survey, the U. S. Weather Bureau and the chiefs of the many municipal water supply works around the Great Lakes will each help toward better records in the future.

WATER CURRENTS IN THE GREAT LAKES

These currents are of present interest because of their influence upon the temperature of the water and consequently upon evaporation.

The matter of horizontal currents circulating within the Great Lakes had been previously investigated by Mr. Normand B. Conger who found fairly definite and persistent currents of broad reach. His results were published with maps, by the U. S. Weather Bureau.

Colonel Townsend, from this three months study, questioned some of Mr. Conger's methods and conclusions. Mr. Conger, however, has had a longer and more intimate experience, on these lakes, and has made more observations on floats, and the present writer finds from recent conference that he still believes that his views on horizontal rotation of surface currents are well supported by various facts.

For some years prior to the Weather Bureau taking over this work, the Signal Service published elaborate monthly bulletins in the form of large maps, regarding wind, weather, currents and number of foggy days over the Great Lakes. These were discontinued about 1913. On these maps these currents are shown revolving horizontally, with a wide sweep.

RECENT OBSERVATIONS ON CURRENTS

By Frank Jermin, Meteorologist, at Alpena, Mich.

Currents in the Great Lakes, as a menace to navigation, are discussed by Frank Jermin, meteorologist, on page 18 of the annual report of the Lake Carriers Protective Association for 1823, with an earnest recommendation that they be given more thorough study than that of 1892, when they were charted by bottle papers in a general way.

Now, with the development of the radio, it is thought that with further study, warnings regarding the changing currents could be sent out to mariners from the nearest Weather Bureau Station in time of fogs, which would be of great practical service in aiding them to hold their proper course and path, or to correct for drift.

The currents were found, by enquiry from fishermen and mariners, to vary in direction from day to day, and were **not always running with the wind;** particularly in the vicinity of Thunder Bay Island, where the fishermen are convinced, from the debris sometimes caught in their nets and the tearing they sometimes receive, and from other indications, that strong currents sometimes are set in motion at depths of from 100 to 200 feet, in times of only moderate wind.

July and August are called the months of currents.

These currents in the water seem somewhat analogous to sudden eddies and currents in the air, sometimes produced by high barometric gradients, and some remarkable instances are cited of strong currents developed during local squalls.

Mr. Jermin believes that currents which occur during fogs are a prolific cause of marine disasters, by throwing vessels off their course.

(Additional comments by Mr. Jermin on the cause and effect of lake currents are given on page 187.)

HEIGHTS OF WEATHER BUREAU INSTRUMENTS AT STATIONS ABOUT THE GREAT LAKES

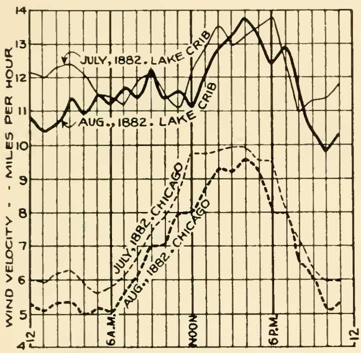
Station	Location. Street and Name of Building	Elev. of Barometer Above Sea Level	Elev. of Barometer Above Lake Level	Approx. Elev. of Ground at Station	Approx. Elev. of Ground Above Mean Lake Level	Height, in Feet, of Instruments Above Ground: Thermometer	Rain Gage	Anemometer	Anemometer Above Lake Level
Lake Superior			(–603)		(–603)				
Duluth	Weather Bureau Bldg., 7th Ave., W.	1133	530	1127	524	5	3	47	571
Marquette	Savings Bank Bldg. Cor. Washington & Front Sts.	734	131	652	49	77	70	111	160
Houghton	Masonic Temple, corner Sheldon and Portage Sts.	668	65	643	40	62	57	99	139
Sault Ste. Marie	Portage Ave., West Gov't Grounds	614	11	606	3	11	3	52	55
Lake Michigan			(–582)		(–582)				
Escanaba	P. O. Bldg., Ludington St.	612	30	592	10	54	44	60	70
Green Bay	Minahan Building, 210–216 E. Walnut St.	641	35	588	6	109	101	141	147
Ludington	First Nat. Bank Bldg., Cor. Ludington Ave. and James St.	637	55	605	23	60	53	66	89
Grand Haven	Masonic Temple, Washington and Third St.	632	50	605	23	54	49	89	112
Milwaukee	Federal Bldg., Room 416.	681	99	619	37	125	117	139	176
Chicago	Federal Building at Adams, Dearborn, Jackson and Clark Sts.	823	241	594	12	140	133	310	322
Lake Huron			(–582)		(–582)				
Alpena	Federal Building, 135–145 Walnut St.	609	27	587	5	13	4	92	97
Port Huron	Public Bldg., cor. Water and 6th St.	638	57	599	17	70	63	120	137
Lake Erie			(–574)		(–574)				
Detroit	Majestic Bldg., cor. Mich. Ave. and Campus Martius	730	156	600	26	218	214	258	284
Toledo	Nicholas Bldg., cor. Madison Ave. and Huron St.	628	54	589	15	208	201	243	258
Sandusky	P. O. Bldg., cor. Columbus Ave. and Market St.	629	55	594	20	62	54	70	90
Cleveland	Society for Savings Bldg., Public Sq.	762	88	659	85	190	165	201	286
Erie	Commerce Bldg. Cor. 12th and State Sts.	714	140	670	96	130	122	166	262
Buffalo	Telephone Bldg., 44 Church St.	767	193	603	29	247	238	280	309
Lake Ontario			(–247)		(–247)				
Rochester	U. S. Gov't Bldg. cor. Church and Fitzhugh Sts.	523	275	493	226	86	77	102	328
Oswego	Customs House, Oneida St.	335	88	292	45	76	68	91	136

There is a slight confusion in the records of Weather Bureau Station data, in the elevation of station, because when a station at a particular city is moved from one tall building to another, the original "nominal elevation" sometimes persists in the record, although proper compensation is made for the difference in the barometric record as reduced to sea level.

DATA ON WIND VELOCITY AT WATER SURFACE OF GREAT LAKES COMPARED WITH THAT AT WEATHER BUREAU STATIONS

Comparisons of Wind Velocity Over City and Lake at Chicago 43 Years Ago by U. S. Signal Service

Velocities of winds at Chicago,* over Lake Michigan, on the intake crib of the water works, out about 3 miles from shore, at an elevation of six feet above the roof of the keepers house, and 37 feet above the lake surface, were compared with the simultaneous velocities of winds measured at 105 feet above the ground on top of a tall building, which was unobstructed by other near-by buildings of equal height, although doubtless the wind here was somewhat retarded by the irregular outline of roofs not far below.



DIURNAL RANGE OF WIND VELOCITY AT THE LAKE CRIB AND AT CHICAGO.

These comparisons, which continued from March 1 to September 30, 1882, are reported in Signal Service Notes No. VI, printed by authority of the U. S. War Department. The two anemometers subsequently compared side by side gave practically equal total mileage in a ten day test.

In brief it was found:

(1) The wind velocity 37 feet above the water at the lake crib at night, or from 11 p. m. to 6 a. m., was **double that over the city,** shown by an anemometer 105 feet above the ground.

This difference gradually diminished until noon, when the wind over the lake was only about ⅓ greater than over the city.

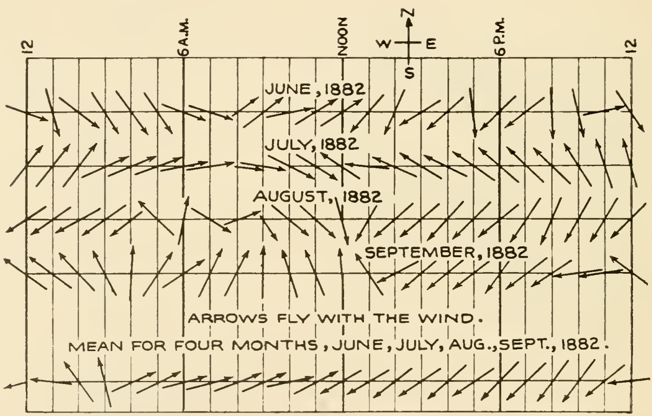
(2) From April to September, the mean wind velocity at the crib averaged 60% greater than over the city. In other words, with 16 miles per hour recorded over the city, the velocity over the lake was 25 miles.

*The elevation of the anemometer at the Chicago station at the time of the observations refered to in 1882, was 103 feet above ground. The Chicago office was not moved into the Auditorium Building until November 1, 1890, when the elevation was increased to 274 feet. However, the Chicago office was again moved on January 1, 1905, to the Federal Building, where the elevation of the anemometer was 310 feet.

(3) The diurnal range of the wind velocity at the lake crib, is about half that over the city, which may be accounted for by the well defined breeze alternating from land to lake, and lake to land, and the less heating of the air over the lake.

(4) Winds from the east, southeast, south and southwest give more nearly equal velocities over city and lake.

The following drawing illustrates the hourly, and alternating shift from lake to land, at Chicago.



MEAN HOURLY DIRECTION OF THE WIND AT CHICAGO, ILL.

Showing Winds from off the Lake in Afternoon and from Land to Lake until Noon

Because of lack of information the wind velocity, as affecting evaporation over each of the lakes, **has been assumed for the present the same as the average of Weather Bureau records,** although probably it would be nearer the truth to call it at least 25% greater.

Down closer to the water the wind velocity would be perhaps only 80% of that 37 feet above, or in general, say 0.80 x 1.60 = 1.28 or 28% greater over the lake than at this Signal Service weather station of 1882, 103 feet above ground, at corner of LaSalle and Madison Streets.

The present Weather Bureau station in Chicago is reported to have its anemometer 310 feet above the ground and 322 feet higher than the lake surface, but meanwhile the surrounding buildings have become taller.

Additional information about the relation of wind velocity in contact with the lake surface to that at the Weather Bureau stations is greatly needed.

On enquiry of the Chicago Water Works management, it is learned that an air anemometer has been procured at one of the intake cribs but not yet connected up for service.

Wind Comparisons at Buffalo

A series of observations upon velocity of the wind 65 feet the level of the lake, on the Buffalo breakwater, at the eastern end of Lake Erie, compared with that at the neighboring Weather Bureau station at an elevation of 308 feet above the lake, is given in the *Monthly Weather Review* of April 1917, by Mr. Benjamin C. Kadel, an expert Meteorologist of the U. S. Weather Bureau.

Mr. Kadel states that this anemometer at the Weather Bureau office has "one of the most free exposures in the United States," being upon a 40 foot steel tower on top of the N. Y. Telephone Building. The instrument at the lake, exposed upon a cross-arm of the flagstaff at the Coast Guard Station, 65 feet above the lake, gave in general **about 78 per cent** of the wind velocity found at the elevation of 308 feet. It was thought that possibly in the case of winds coming down the lake, there was a "banking up," of the wind at the Coast Guard Station, near the shore, due to the presence of the city buildings a little farther on.

Common experience with falling leaves, dust particles, snowflakes, etc., shows that with a breeze upward of 5 miles per hour, the air in contact with the ground and up to 10 feet above the ground (perhaps up to 50 feet), mostly is in a **state of turbulence, eddys, and vertical rotation, influenced by the roughness of surface.** When wind velocities are high, roughness of lake surface is caused by waves. This turbulence of the air, which doubtless quickly lifts vapor-laden air from a broad open water surface to higher levels, is not revealed by the anemometer, but can be shown by chemical fumes, the ascent of which is not caused by heat.

The writer has found useful, in various experiments on air currents, the dense white flumes of ammonium chloride, easily produced by pouring hydrochloric acid into a cup and aqua ammonia into its saucer.

A few drops of titanium tetra chloride by itself, or dropped slowly into a small dish containing water, also gives dense white fumes, very slightly heavier than air, useful in revealing air currents.

At the Rochester reservoir, a comparison of average monthly values for a term of years shows the wind velocity at the anemometer 3 feet above water on the float beside the evaporation tank, consistently was **about 68 per cent** of the velocity shown at the Rochester station of the U. S. Weather Bureau, some distance away.

At Boston, a comparison with the Weather Bureau anemometer on top of the Post Office Building about 5 miles away, on all days for which wind records are given in Mr. Fitgzerald's paper for his anemometer upon the shore of the reservoir, 30 feet above the water, shows the anemometer at the reservoir consistently giving **about 70 per cent** of the velocity by the elevated Weather Bureau anemometer.

This matter of relation of wind velocity over the lake surface to that at the adjacent Weather Bureau station could be accurately determined once for all, by setting anemometers, simply provided with revolution counters, on the tops of the outermost piers, breakwaters or cribs at each of the larger lake harbors, and making comparison with the Weather Bureau records during typical periods of winds blowing from off the lake, and, of winds off the shore. Similar observations and comparisons at light houses and light ships around the lakes, near the water line (also accompanied by other observations as high as practicable), would be useful in a future more accurate estimate of depth of water evaporated.

Recording anemometers, set low, near the forward end of a car-ferry, or other boat, could readily be corrected for speed and course of boat and would give useful information about mid-lake winds in comparison with the breezes from water to land by day, and from land to water by night; which probably run only a relatively short course.

Relations of Velocity at Water Surface to Velocity by Anemometer Set 30 Feet Above

Questions have been raised as to the actual velocity of the wind at the surface of the floating tanks, used in Mr. Fitzgerald's experiments near Boston in which his anemometer was not set on the raft near the water, but was on the shore at about 30 feet above the water.

The following approximate formula for computing the relative velocities of wind at various heights above the surface, is given on page 35 in the "Treatise on Weather Forecasting in the United States," published by the U. S. Weather Bureau in 1916:

$$V = v\sqrt{\frac{H+72}{h+72}}$$

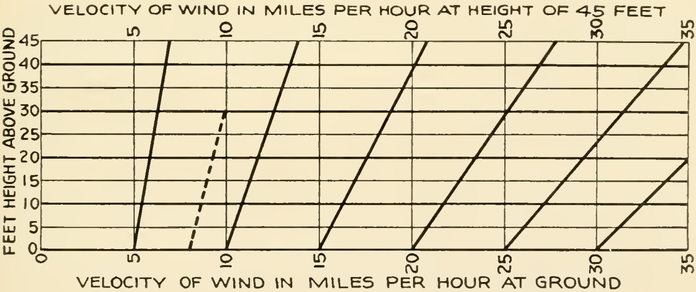
in which, V is the velocity wanted at height H in feet above ground, and v is the velocity observed at height h in feet above ground.

One would expect from this formula, that having given the velocity of 10 miles per hour by Mr. Fitzgerald's anemometer at 30 feet above the ground, on the shore of the Boston Water Works reservoir, the true wind velocity at 1 foot above his raft, close to his floating evaporation tank, would be about,

$$V = 10\sqrt{\frac{1+72}{30+72}} = 8.16$$ miles per hour, **or 82% of** Mr. Fitzgerald's anemometer reading.

Professor Frank H. Bigelow of the U. S. Weather Bureau, investigated the relation of wind velocities at different heights, in course of his elaborate study on evaporation at Reno, Nevada, published in the Monthly Weather Review for February, 1908.

He used 5 towers, each 45 feet in height, and 13 anemometers distributed at top, and bottom of these towers and some placed midway, adjacent to his evaporation pans. His deduction of relations found between the wind currents at various heights from the ground up to 45 feet are shown in the diagrams below. He published no details showing the scatter of his observations.



RELATION OF VELOCITY OF WIND AT GROUND AND AT HEIGHT OF 45 FEET.
AS FOUND BY PROF. FRANK H. BIGELOW AT RENO, NEVADA.

Altho these observations by Bigelow are not sufficient for indicating the relation between the velocities at the elevated Weather Bureau stations and those at the surface of the Great Lakes, they serve to confirm the expectation that the wind velocity at Mr. Fitzgerald's 10-foot floating tank in the midst of reservoir should have been **about 80% of the velocity given by his anemometer, on shore, elevated 30 feet above the water.** This agrees closely with the result by the above formula.

DATA ON INFLUENCE OF VELOCITY OF WIND UPON EVAPORATION

There is surprisingly little dependable experimental data on the precise amount by which evaporation is increased by an increased velocity of the wind.

It is plain that the rate of evaporation must depend largely upon the rate at which the film of chilled and partially saturated air, at the surface of the water, is replaced by the wind. Although it has been thought that the diffusion and dissipation of the vapor generated would be rapid, even in still air, this is not borne out by experiment. One might expect that a slight puff of air would remove the slight vapor blanket from the surface of an evaporation pan in which water is slightly below the top, but Dr. Marvin has suggested that its adhesion is persistent.

It is a matter of general experience that evaporation is increased by the wind. The present question is regarding the precise rate of increase in evaporation, in inches depth per hour, for each mile per hour of increase in velocity of wind.

The only important data of quantitative character found on wind effect are:

(1) The original experiments of Dalton, with crude descriptions of wind velocity.

(2) Fitzgerald's laboratory experiments reported in Table 5, page 643, Tranactions of the Am. Soc. C. E. for 1886.

(3) Measurements of wind velocity concurrent with Mr. Fitzgerald's experiments with tanks floating in an 85-acre reservoir.

(4) Observations of evaporation and wind velocity at Rochester, N. Y. reservoir; from a very small floating tank, with anemometer three feet above water.

(5) Professor Thomas Russell's experiments with the Piché evaporimeter moved thru the air at various velocities, reported in the Monthly Weather Review for September, 1888.

(6) Professor Bigelow's experiments at Reno and at Salton Sea, reported in the Monthly Weather Review of July 1907, February 1908, and February 1910, and the Weather Bureau Summary for 1908.

(7) Experiments by Professor Carpenter of the State Agricultural College at Fort Collins, Colorado, published as a Report of Colorado Agricultural Experiment Station in Bulletin No. 45, May 1898.

(8) Observations at Keewatin, Lake of the Woods, Ontario, reported in Canadian Water Resources Papers No. 22, 24, 26, 31, 36, 40 and 44.

(9) Studies regarding a new formula for evaporation, by Professor C. F. Marvin, Director, U. S. Weather Bureau, February 1909 and April 1909.

Dalton's Experiments on Wind Effect

(1) Dalton's experiments were with a tin dish 6 inches in diameter and half an inch deep, filled with water, from which evaporation was determined by careful, precise weighing, before and after exposure to: (a) gentle draft of air, (b) moderate breeze, (c) brisk wind.

These terms probably corresponded to velocities, at the water surface, not far from 5 miles, 10 miles and 15 miles per hour, possibly a little less.

Dalton's data were obtained by measuring the temperatures of air and the dew-point carefully, during numerous experiments in which he determined the loss of weight in grains of avoirdupois, as a method of finding the quantity evaporated in a given time from a water surface in a tin dish 6 inches in diameter, and one-half inch deep. In other experiments on a small dish filled with water held barely below the boiling point, he measured the loss of weight for three different rates of air movement:

(1) A gentle draft, (2) a moderate breeze, (3) a brisk wind.

Dalton's experiments were on a small scale and with extremely simple apparatus; but he accomplished more than any of his predecessors and more than most of his followers. It has been said of all of Dalton's researches, that they "were made more with his head than with his hands."

There have been so few good data put on record in all of the 125 years that have followed, that it is desirable to put Dalton's values alongside the later determinations. Some uncertainty attaches to these three terms used by Dalton in describing velocity of wind, but one will not be far wrong in assuming the first equivalent to from four to six miles per hour; the second, from eight to ten miles per hour; and the third, from 12 to 15 miles per hour, as may be judged from tables below.

The Beaufort scale, in popular use for about a century, and long used by the U. S. Weather Bureau in forecasts and descriptions of force of wind is given on the next page.

It is of interest to remember that velocities of currents of air smaller than about 4.4 feet per second, or 3 miles per hour, are barely perceptible to the senses, and are classed as "calm."

A velocity of 1 foot per second is imperceptible to the senses, unless aided by the exposure of a slightly moistened finger to its chill, or by the motion of motes as in a sunbeam.

A column giving the equivalent velocity of the wind in feet per second, and another column giving the equivalent pressure of the wind in pounds per square foot, have been added by the present writer.

Popular Description of Force of Winds of Various Velocities

(From "Instructions to Marine Meteorological Observers", Circular M, U. S. Department of Agriculture, January, 1925)

Beaufort number	Velocity of Wind: Miles per hour Statute	Velocity of Wind: Feet per Second	Pressure in Lbs. per Sq. Ft.	Explanatory Titles	Mode of Estimating aboard sailing vessel	Specification for use on land
0	Less than 1	Less than 1.47	Less than .005	Calm	....	Calm, smoke rises vertically.
1	1 to 3	1.47 to 4.4	.005 to .045	Light air	Sufficient wind for working ship.	Direction of wind shown by smoke drift, but not by wind vanes.
2	4 to 7	5.8 to 10.5	.08 to .241	Slight breeze		Wind felt on face: leaves rustle, ordinary vanes moved by wind.
3	8 to 12	11.7 to 17.6	.315 to .708	Gentle breeze		Leaves and small twigs in constant motion; wind extends light flag.
4	13 to 18	19.1 to 25.7	.845 to 1.62	Moderate breeze	Forces most advantageous for sailing with leading wind and all sail drawing	Raises dust and loose paper; small branches are moved.
5	19 to 24	27.8 to 35.2	1.81 to 2.88	Fresh breeze		Small trees in leaf begin to sway; crested wavelets form on inland waters.
6	25 to 31	36.6 to 45.4	3.12 to 4.80	Strong breeze	Reduction of sail necessary with leading wind.	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty.
7	32 to 38	46.9 to 55.7	5.12 to 7.21	Hight wind (*Mod. gale*)		Whole trees in motion; inconvenience felt when walking against wind.
8	39 to 46	57.1 to 67.5	7.60 to 10.6	Gale (*Fresh gale*)	Considerable reduction of sail necessary even with wind quartering.	Breaks twigs off trees; generally impedes progress.
9	47 to 54	68.8 to 79.1	11.05 to 14.60	Strong gale		Slight structural damage occurs (chimney pots and slate removed).
10	55 to 63	80.6 to 92.3	15.15 to 19.85	Whole gale	Close reefed sail running, or hove to under storm sail.	Seldom experienced inland; trees uprooted; considerable structural damage occurs.
11	64 to 75	93.8 to 110.	20.5 to 28.1	Storm		Very rarely experienced, accompanied by widespread damage.
12	Above 75	Above 110	Above 28.1	Hurricane	No sail can stand even when running.	....

The pressures per sq. ft. in the above table corresponds to the formula

$$P = 0.005V^2$$

in which V is the velocity of wind in miles per hour.

If we accept 5 miles, 10 miles and 15 miles per hour as the average velocities of his air currents, we may express Dalton's results by the formula that follows and they fit well with the latest data.

Evaporation in 24 hours $= E = (V-v)\ (0.5 + 0.05W)$

It should be remembered, however, that Dalton himself used no formula, but presented a vapor pressure table and described how it could be used to estimate evaporation.

Dalton also considered the effect of barometric pressure upon evaporation, and reasoned that this retarded evaporation, only to the extent that a high barometric pressure interposed more particles of air in the path of the escaping particles of vapor; which would obstruct its flow very much as water discharged down through a mass of pebbles would be obstructed by the pebbles and have its velocity reduced in passing between them.

While the general correctness of Dalton's laws of evaporation seems to have never been seriously disputed, there are certain supplementary facts to be considered, for which new precise experimental data are greatly to be desired. These relate chiefly to circulation and renewal of films of air and water at the surface of contact.

The vapor pressure in the air which opposes evaporation must, in the absence of forced circulation, be measured at some point very near the surfaces in contact in order to give a correct measure of the rate of evaporation.

When there is no external force moving the air, other than the slight levitation due to the lessened specific gravity of moist air compared with dry air, the humidity of the air at the surface in contact will quickly become increased, and evaporation greatly retarded by this partial saturation and also by the chilling of the surfaces in the process of vaporization, unless this chilled and saturated air is removed very promptly, by forcibly supplying a quantity of fresh air against the evaporating surface.

In the laboratory, the natural movement of this fresh supply is feeble and irregular.

On the open lake, the ordinary force of the wind, averaging 8 or 10 miles per hour, causes the action needed.

The Fitzgerald Experiments on Wind Effect

(2) The Fitzgerald experiments, reported in his table No. 5, were made for the special purpose of determining the effect of wind upon the rate of evaporation, and were made under a roof; but practically in open air, since the building shown in his photograph, has no side walls.

His anemometer was on a table beside the evaporating pans, about 3.5 feet above the floor. Evaporation was measured by determining the loss of weight from each of three pans exposed simultaneously, each pan being 14.85 inches in diameter and one inch deep. Each pan rested upon, and was surrounded by, a water bath, within which heated water could be circulated to control the temperature of the water in the evaporating pan.

Apparently one evaporating pan was kept at about normal temperature of the outside air (about 59 to 71 degrees F.); another, at from 90 to 100 degrees; and the third, from 110 to 115 degrees.

Wind swept past naturally, at rates varying from about two miles to about 11 miles per hour.

In order to determine the wind coefficient in a formula of the Dalton form, for each of the experiments described in Mr. Fitzgerald's Table 5, the observed rate of evaporation per 24 hours has been divided by the vapor pressure factor (V-v) thus obtaining as the quotient a coefficient which includes both the evaporation factor and the wind factor. The values thus found were plotted on the diagram reproduced on page 136. They show increase in evaporation with increased velocity of wind, substantially along a straight line, for winds upward of four miles per hour.

The line indicating the wind factor and coefficient, for these experiments of Mr. Fitzgerald **which were made at normal temperatures,** intersects the base at about 0.80, and has a slope at the rate of 0.063 W; but the observations scatter so, that a line could be drawn fairly close to the several points which would intersect the base at 1.0, and, have a slope of very nearly 0.05 W.

The amounts evaporated simultaneously from the adjacent pans under higher temperature, are shown on the same diagram; and although the coefficients shown for these warmer pans are from 10 to 20 per cent smaller than for the pan containing water at the temperature of the surrounding air, they follow, in a general way, the same general law of increase in evaporation proportional to increased velocity of wind.

In Mr. Fitzgerald's series of laboratory experiments in the open air with the wind blowing and its velocity measured by anemometer, it would seem this condition of an obstructive vapor blanket, would not prevail in the experiments reported in his table No. 5, page 643, in which the wind velocity commonly ranged from two miles per hour up to 13.8 miles per hour. His pans were kept very nearly full.

If the observations made on water at about the atmospheric temperature are plotted separately, **those above velocities of 4 miles per hour fall nearly on a straight line,** the equation of which may be expressed by the formula

$$E = (V - v)(1 + 0.05W).$$

The experiments on tank No. 1, when the recorded wind velocity is divided by 3 as suggested by Mr. Fitzgerald, when plotted also fall on this line.

At the actual wind velocities which existed close to the evaporation pans during most of these experiments and recorded in Mr. Fitzgerald's Table No. 5, one would expect that any vapor blanket would be quickly dissipated from over these small well-filled pans, and that conditions for large evaporation would be particularly favorable. It is a fact that evaporation commonly goes on at a larger rate from small pans in laboratory observation, than from large pans out-of-doors.

No other explanation is suggested now, as to why the wind factor in these particular experiments should have been larger than would be found on a large open reservoir; nevertheless, that this wind factor found by Mr. Fitzgerald's experiments on small laboratory pans was exceptionally large, as compared with open air observations, seems borne out from many other observations.

(3) In all of Mr. Fitzgerald's observations upon the evaporation from the large floating tank in the reservoir, the wind effect is so confused with the temperature effect; and the measurement of depths lost in 3 or 4 hours is so small, that **the two effects of warmth and wind cannot be separated** in the hourly records in these observations. Wind velocity and temperature both increased together; both increase following the rising of the sun, and both fall at night.

Taking these Fitzgerald out-door experiments as a whole, and summing up the daily total depths of evaporation for comparison with the daily average of wind velocity, they show much smaller evaporation than Fitzgerald's Laboratory experiments, if the records of the near-by wind gage are taken at face value. They can be plotted in line with the laboratory experiments above mentioned only by accepting as a fact that the wind velocity at the surface of the tank was only about one-third part of that at the neighboring anemometer on shore, 30 feet high, which Mr. Fitzgerald believed was true. Such a relation beween velocity at ground level and at 30 feet above, is contrary to ordinary experience. Many other observations, and the formula and observations cited on preceding pages, indicate that the ordinary relation under such conditions would give at the water surface, 80% of the amount recorded simulatneously by an anemometer up 30 feet. **If these Fitzgerald experiments on the tank in the reservoir are plotted with 80% of the recorded wind value they fall nearly in line with various other data on evaporation.**

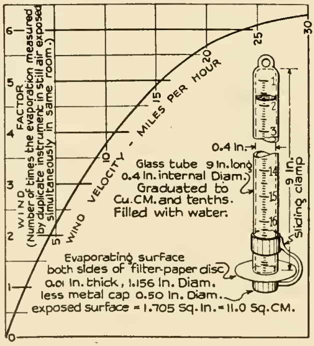
A third test line on this diagram showing rates of evaporation to wind, can be had by taking the mean evaporation in each calendar month of the year from Mr. Fitzgerald's curve as finally adjusted, and plotting these, after dividing as before by (V-v). It is found by taking the average ratio for all of the days upon which Mr. Fitzgerald reports wind velocity and evaporation, that the record by his anemometer was 70% of the record at the U. S. Weather Bureau station in Boston five miles away. Applying this 70% to the further ratio of 80% commonly found for a difference in height of 30 feet above the ground, we would have a total correction factor of 56%; but there seems to be something anomalous and unexplained about the wind ratios here. The writer has conferred with Mr. Fitzgera'd and with the chief engineer of the Boston Water Supply in trying to go back to the more complete original records, but they can not now be found, 40 years after being filed away.

It will be noted, that although these Fitzgerald experiments with floating tank in the midst of the reservoir agree tolerably well among themselves, the average values for wind factor for this series as a whole is much lower than in the experiments previously described.

Rochester Observations—Effect of Wind on Evaporation

(4) Next in the effort to find data upon the wind effect, the observations at Rochester are plotted on the same diagram, in terms of the reading by the anemometer beside this evaporating tank, three feet above the water surface. Months are omitted in which the Rochester tank was covered with snow or ice.

(5) Next an effort was made to find a measure of the effect of wind upon the rate of evaporation through Professor Russell's experiments upon increase of evaporation caused by increased velocity of the Piché evaporimeter on a whirling machine. Although this instrument seems better adapted to represent evaporation by transpiration, as from a growing leaf, than that from a large water surface, these experiments are interesting, but not conclusive.



PICHÉ EVAPORIMETER
As used by Prof. Russell

These Piché wind experiments were made in a closed room which was abnormally hot and dry, in comparison with the climate in the Atlantic states, or the climate about the Great Lakes, but had air temperature and humidity more representative of climatic conditions found around the Salton Sea, or summer temperatures around many reservoirs of the semi-arid west.

Professor Russell's rates of increase of evaporation found with increased velocity, possibly were reduced by the failure of the thin sheet of filter paper, comprising the evaporating surface in the Piché instrument, to conduct water from the reservoir to the instruments as fast as it could be evaporated in dry air at high velocity. This has been one of the recognized defects of the Piché instrument as heretofore constructed.

The Piché instruments used in 1907 by Professor Bigelow (Monthly Weather Review of February 1908, page 38) were of an improved form, having a Mariotte tube for giving constant head of water, and a larger paper disc. Their larger disk of filter paper was found incapable of delivering watei sufficiently fast to supply evaporation from its surface at the higher wind movements, or at a high rate of evaporation such as due to dry air or strong wind.

He noted that the temperature controlling the evaporation from the Piché instrument was strictly that of a wet-bulb thermometer; and the vapor pressure difference, only that between the wet-bulb and the dew-point temperatures.

In this connection reference may be made to the graphical log of the Fitzgerald observations on page 481, for showing how small this difference between the temperature of the wet-bulb and dew-point is in comparison with that between the vapor pressures at water temperature and at dew-point temperature, and the consequent smaller precision of measurement of rate of evaporation by the Piché method.

Professor Russell also noted, incidentally, that the energy for evaporation must come from the heat of the surrounding air. Also that the effect of lessened barometric pressure, as at high altitudes, would be expected to cause evaporation to become greater in direct proportion as pressure becomes lower. Also that the energy required in expanding the vapor is equal to the product of the pressure by the volume of vapor produced.

Professor Russell does not state the amount which he found evaporating from the duplicate Piché instrument in still air, under the same humidity and temperature as that of the air around the instrument on the whirling machine, but this may be estimated by working backward from his statement of a humidity of 50% and a temperature of 87°F.; which gives a dew point of 63.2 degrees, and according to Russell's formula would give under these conditions an evaporation of 0.362 inches per 24 hours.

On attempting to plot this with Professor Russell's values at various velocities on the same diagram with experiments previously described, the points for 5, 10 and 15 miles per hour show coefficients for wind effect greatly in excess of those of the Boston and Rochester experiments.

It is of interest to note that in his own final adjustment of estimates for evaporation at stations throughout the United States, **Professor Russell did not make use of a separate wind factor;** and that in comparing wind velocity and estimated depth of evaporation at the various stations, he found no consistent relation, and therefore **he included no wind factor in his formula.**

He states that the average of wind velocities at all of these Weather Bureau stations was about 7.1 miles per hour and that the wind inside the thermometer shelters where his Piché instruments were exposed, was presumably only of about one-third of this velocity of 7.1 miles per hour outside.

One chief object of Professor Russell's investigation was comparative results, and his methods of estimate were the same for all stations.

The Bigelow Observations on Effect of Wind on Evaporation

(6) The experiments by Professor Bigelow at Reno and at Salton Sea were not satisfactory in giving an accurate measure of the effect of the wind in increasing evaporation. The wind at Reno was extremely variable from hour to hour, rising in the morning and increasing with the heat, and dying down at night. The effect of the greater wind velocities of the day was so confused with that of temperature, that it appeared impossible to make a separation. At first Mr. Bigelow thought the wind factor could be represented by:

about $(1+\frac{W}{35})$, but later changed this to about $(1+\frac{W}{9})$.

His experiments are unfortunately inconclusive. His methods lacked precision in measurement of the microscopic depths evaporated from hour to hour, and the effects of several different causes were confused in the final measurement.

In the paper of July 1910, Professor Bigelow tells of lack of success with wind coefficients derived from the Reno experiments.

The Carpenter Observations on Wind Effect

(7) Next the published records of the observations on evaporation by Professor Carpenter were examined, in hope of finding new data on wind effect, without any noteworthy success. The floating pans were only one foot square, the water level commonly was about 4 inches below the rim, and the wind was measured at the college, from 2 to 4 miles away. Moreover, climatic conditions were very different from those found about the Great Lakes.

New Experiments Needed

It appears readily possible to make conclusive laboratory experiments on the effect of wind, in a small inexpensive wind tunnel, on a pan, say, 4 ft. in diameter by 2.5 ft. deep, with top set flush with the floor; by creating the required velocities by an electrically driven fan, and being careful as to size, shape and exposure of the evaporating pan, keeping note, meanwhile, of the temperature and dew-point of the air; and continuously circulating the same air in a large closed room, which could be varied in temperature and humidity as desired. Also the water temperature could be varied by mixture with finely cracked ice.

Also, it would be instructive to agitate the water within the evaporating pan in some of the experiments, as in the case referred to by Professor Carpenter, in which a French engineer, found this increased the evaporation about one-third.

RELATION OF TEMPERATURE AND HUMIDITY OF AIR AT MID-LAKE TO THAT RECORDED AT WEATHER BUREAU STATIONS ON SHORE

A feature regarding wind movement over the lakes that is of particular interest in reference to humidity of air measured in summer, at Weather Bureau stations about the lakes, is noted by Mr. P. Vedel, in a paper before the Western Society of Engineers (Vol. 1–1896–p. 405), read June 3, 1896:

> "A notable feature is the regularity of the lake breezes, which blow toward land during the day time, in summer usually from 8 to 10 a. m. to sunset; and the land breeze toward the lake during the night in summer, from 9 p. m. to 10 p. m. until sunrise."

This alternation of direction of wind at Chicago is shown very plainly by the diagram on page 462.

Apparently, the larger humidities from off-lake winds which occur by day, would figure larger in the record than the night observations with off-shore winds, because of their relation to the customary hours of observation, and thus would automatically help the ordinary Weather Bureau record toward taking proper account of the effect of the lake upon the temperature and humidity of the air; particularly during the months of largest evaporation.

Comparisons of Temperature and Humidity on Windward and Leeward Side of Lake

Comparison of observations made at the same time on opposite sides of Lake Michigan, at Milwaukee, and at Grand Haven or Ludington, when wind is first from the west and then from the east, as in the following table, shows the extent to which the wind has become cooled, or loaded with moisture, while crossing the lake.

The humidity and vapor pressure differences, which primarily control evaporation are fairly well represented in the observations recorded at the Weather Bureau stations at the borders of the lake, because for about half of the time the wind reaching these stations has come across the lakes.

Weather Bureau Stations are distributed in nearly equal proportion on both sides of each lake.

To test this matter and find how great the difference is in temperatures of air and water, and in humidity, and in probable depth of evaporation, the following 24 examples in the year 1911 were compiled with the data on water temperatures contained in the report of Colonel Townsend in combination with humidities as observed at the U. S. Weather Bureau stations.

For an additional check, a series of dates in spring, summer and autumn of 1923, or 12 years later, comprising 19 examples, with winds from the west to east, and 22 examples with winds from east to west were worked out from the data of the U. S. Weather Bureau, which give the results as given in the following table.

In this second series, of 1923, there being no recorded temperature of water, it was assumed that in each case the differences between the two sides of the lake averaged the same as under similar conditions in the Townsend observations.

Contrary to first expectations, **the factors promoting evaporation are found stronger on the leeward than on the windward side.**

EFFECT ON AIR OF CROSSING LAKE MICHIGAN

Temperatures, Wind, Humidity, etc. Observed at Grand Haven Compared With Those Observed on Same Day at Milwaukee

	Wind, West to East		Wind, East to West		
	Average of 10 Days June July August September 1911	Average of 19 days Spring Summer Autumn 1923	Average of 11 days June July August September 1911	Average of 22 Days Spring Summer Autumn 1923	Grand Average
Average velocity wind, miles per hour, on windward side	7.9	8.5	8.2	9.9	8.6
On leeward side	9.6	11.4	10.8	10.8	10.6
Average temperature air on windward side	82.0°	62.0°	73.1°	58.5°	68.9°
Average cooling of air in crossing lake, due evaporation, etc.	8.9°	3.2°	1.1°	1.9°	3.8°
Average temperature of water on windward side	65.3°	54.8°*	61.3°	53.3°*	58.7°
Water found warmer on leeward side (Return current brings cooler water to surface on windward side.)	1.5°	1.2°	1.4°	1.5°	1.4°
Water on windward side cooler than air	16.7°	7.2°	11.8°	5.2°	10.2°
" " leeward " " " "	6.3°	2.8°	9.3°	1.8°	5.0°
Relative humidity of air on windward side	55.7%	61.0%	69.8%	74.9%	65.3%
Relative humidity of air increased in crossing lake	12.1%	13.2%	3.4%	4.8%	8.4%
Dew-point of air raised in crossing lake	—2.8	+2.2°	+0.3	+0.9°	0.15°
Computed evaporation, depth per month, lessened on leeward side by inches, if all days were like these	—2.71	—0.091	0	—0.453	—0.813

*Estimated from previous observations.

—Very strangely, for almost every day in both series, the evaporation estimated from these data was greater on the leeward side, not withstanding the cooler air and the increased relative humidity.

Apparently the effect of the cooler water, on the windward side, brought up from below by the reverse circulation from that on surface, of water driven before the wind, and the increased wind velocity on the leeward side, offset the factors of greater humidity and lower temperature of air mentioned in the preceding paragraph.

The following analysis of the grand average values in the above table, shows to what factors this greater evaporation on the leeward side of the lake may be attributed.

	Aver. Velocity of Wind Miles per Hour	Corresponding Coeff. in Formula E=(V-v) (0.5+0.05W)	Mean Temp. of Water °F.	Vapor Pressure Due Water Temp. (V)	Mean Temp. of Air °F.	Mean Relative Humidity %	Mean Dew-Point Temp. °F.	Vapor Pressure Due Dew Point Temp. (v)	Difference in Vapor Pressures (V-v)	Computed Evap. per 24 hrs. Inches Depth	Equiv. Evap. per Month Inches Depth
Windward side	8.6	0.93	58.7	0.4936	68.9	65.3	56.7	0.4600	0.0336	0.0312	0.95
Leeward side	10.6	1.03	60.1	0.5188	65.1	73.7	56.5	0.4560	0.0628	0.0647	1.97
Excess on Leeward side	2.0	0.10	1.4	0.0252	—3.8	8.4	—0.2	—0.0040	0.0292	0.0335	1.02

From this summary it is seen that the increase in wind velocity on the leeward side increases the coefficient in the formula $E=(V-v)(0.5+0.05W)$ by 0.10; which indicates an increase in evaporation

On leeward side of.......... 11%
equal to.......... 0.105 in.

With the same wind velocity and the same dew-point temperature on both sides of the lake, the increase in vapor pressure due to water temperatures, from 0.4936 to 0.5188 tends to increase evaporation in the ratio

$$\frac{(0.5188-0.4600)}{(0.4936-0.4600)}=1.75$$

which indicates an increase in evaporation

On leeward side of 75%.......... 75%
equal to.......... 0.712 in.

With the same wind velocity and equal water temperatures on both sides of the lake, the decrease in vapor pressure due to dew-point temperature, from 0.4600 to 0.4560, tends to increase evaporation in the ratio

$$\frac{(0.4936-0.4560)}{(0.4936-0.4600)}=1.12$$

which indicates an increase in evaporation

On leeward side of.......... 12%
equal to.......... 0.114 in.

From all of the foregoing, it appears that no error controlling general conclusions, can result from the method that has been followed of adopting values for evaporation based on an average of the observed meteorological quantities at Weather Bureau Stations on opposite sides of the lakes.

Although winds from the west have somewhat greater aggregate movement, those from east and west nearly balance, and any attempt to correct the estimate in detail for effect of vapor blanket, beyond that incorporated in the observations, appears of doubtful utility until better data are available.

It is believed that any lessening of evaporation that can possibly be caused by the presence of a vapor blanket is offset in effect by an increase in evaporation due to the greater wind velocity that prevails over the lakes, than at the data stations.

EFFECT OF VAPOR BLANKETS, LARGE AND SMALL

In estimating the evaporation loss from the Great Lakes, there is some question about the extent to which this loss is made smaller because of the presence of a "vapor blanket" over the water.

Small, thin vapor blankets have been found to hover over the top, or within the top, of small experimental evaporation pans, in closed rooms. **The vapor blanket, about which there is question over the Great Lakes, is of a very different order,** and because of the prevailing winds, there is little opportunity for other than a high vapor blanket or a general fog to form over their surfaces.

This high vapor-blanket, whether visible in form of clouds or fog, or invisible, as dissolved vapor, may exert extremely important influences on evaporation from the lake. Much as clouds prevent frost at night on grain or foliage by intercepting radiation into space, **the invisible vapor-blanket by day is a far more potent screen than is commonly realized, by intercepting heat from the sun, and also by preventing loss of heat by radiation.**

The vapor blanket over the top of a little laboratory evaporation dish, or the thin film of chilled and nearly saturated air which lodges below the level of the rim of an evaporation pan, immediately above the water, presents a problem of a different order from that found over a great lake, upon the surface of which wind blows with a velocity, very seldom below 4 miles per hour, often of 15 miles or more per hour, and averaging about 10 miles per hour; and when the wave crests are broken into white-caps by a breeze of 12 or 15 miles per hour, the evaporation must become still further accelerated.

In these laboratory experiments on a small scale, the severe chill in the thin layer of air, near the contacting surfaces, due the abstraction of heat rendered latent in the process of vaporization, may be more potent than the load of vapor, in preventing its rise and replacement by fresh air.

In a closed room, or with small evaporation pans shielded from wind, or with winds of less than 3 miles per hour, different factors prevail from those which govern evaporation on a broad lake; and data collected in closed rooms, or still air, is mostly of doubtful application, except perhaps as the starting point for a curve that soon will turn upward into a nearly straight line, which it probably will follow until the wind reaches a velocity that will generate waves and white-caps, when the rate of evaporation will again increase, for a space.

The recent treatise of Thomas Preston on "The Theory of Heat" (MacMillan, 1919), page 341, states (evidently in regard to laboratory experiments in a closed room):

"The rate at which vapor is formed depends upon the temperature. For a given temperature it is not, however, proportional to the area of the surface of the liquid as ordinarily exposed, but to the linear dimensions to the surface; and in an open vessel evaporation takes place more rapidly near the boundaries of the surface than at the middle, etc."

"Near the edge of the vessel the vapor pressure decreases more rapidly, and it is here, therefore that the flow is the greatest."

Professor Thomas Russell, in calibrating his Piché evaporimeters in a still room, found his small evaporation test pans extremely sensitive to retardation of evaporation by the vapor blanket held in a depression of more than 1/16th inch depth below the edge of the tin dish 2.5 inches diameter.

The writer has sought with small success for useful data about effect of vapor blankets in absence of visible fog or clouds comparable with the present case, in Professor Bigelow's papers, in the monthly weather Review of February 1908, February 1910 and July 1910, and in the attached report by Mr. Lehman.

Several of the recognized authorities have concluded, largely from observations and experiments for the U. S. Weather Bureau at Reno, Nevada, and at the Salton Sea under Professor Frank H. Bigelow in California, and partly from "average judgment," that a broad lake will give less average evaporation (perhaps only 60%, 70% or 80% as much) throughout the year than that measured from a tank of 3 ft. to 8 ft. in diameter immersed in shallow water near the shore, because of a "vapor blanket" over the lake.

Some experienced observers doubt that it has any important effect in preventing evaporation, notably Mr. Charles H. Lee, who carried on many experiments for the Los Angeles Aqueduct, including many observations on evaporation from Owens Lake, California.

Mr. Lee has told of having failed to find any pronounced effect of a vapor blanket retarding the actual evaporation loss from Owen's lake in southern California, located in the desert east of the Sierras, which has no outlet and the discharge into which can be accurately measured.

The writer is familiar with this country around Owen's Lake, and believes the dry air from the surrounding desert would absorb a vapor blanket so as to lessen its effect, far more than in the region around the Great Lakes. In regions not far from Reno, and of similar climate, the writer often has seen rain falling from high clouds, all re-evaporated before it reached the ground; so dry and absorptive is the air during the day in that region.

Need of Precise Observation for Discovering Laws of Evaporation

To trace out the varying effect upon depth of evaporation from hour to hour, under open air conditions, with the rapidly varying temperature, rising from dawn until noon and then falling during the afternoon and night, together with the changing relative humidity or absorptive quality of the air; requires not only the utmost skill, but apparatus of great delicacy.

The unequal expansion of parts of a recording mechanism, and the difference in linear expansion of tank and cubical expansion of the water within it, all tend to obscure the differences of a few thousandths of an inch in elevation of an unstable water surface in the course of an hour, but it can hardly be believed that the difficulties of establishing a rational formula place it beyond reach.

To illustrate the changes from hour to hour, which have to be averaged in working from monthly means, the following excerpt from Mr. Fitzgerald's curves is presented, in diagram form on the next page, which have been replotted by way of further illustration of the difficulties, in the past, toward the discovery of these physical laws of evaporation. Attention is called to some of the features of special interest, in this hourly log of conditions affecting evaporation, as follows:

(1) Note the rapid change from hour to hour in some of the chief factors:

(a) Rapid change in temperature of air.

(b) Slight change in temperature of water.

(c) Rapid change in relative humidity.

(d) Relatively small change in absolute humidity.

(e) Relatively small change in vapor pressure difference.

(f) Rapid change in velocity of wind.

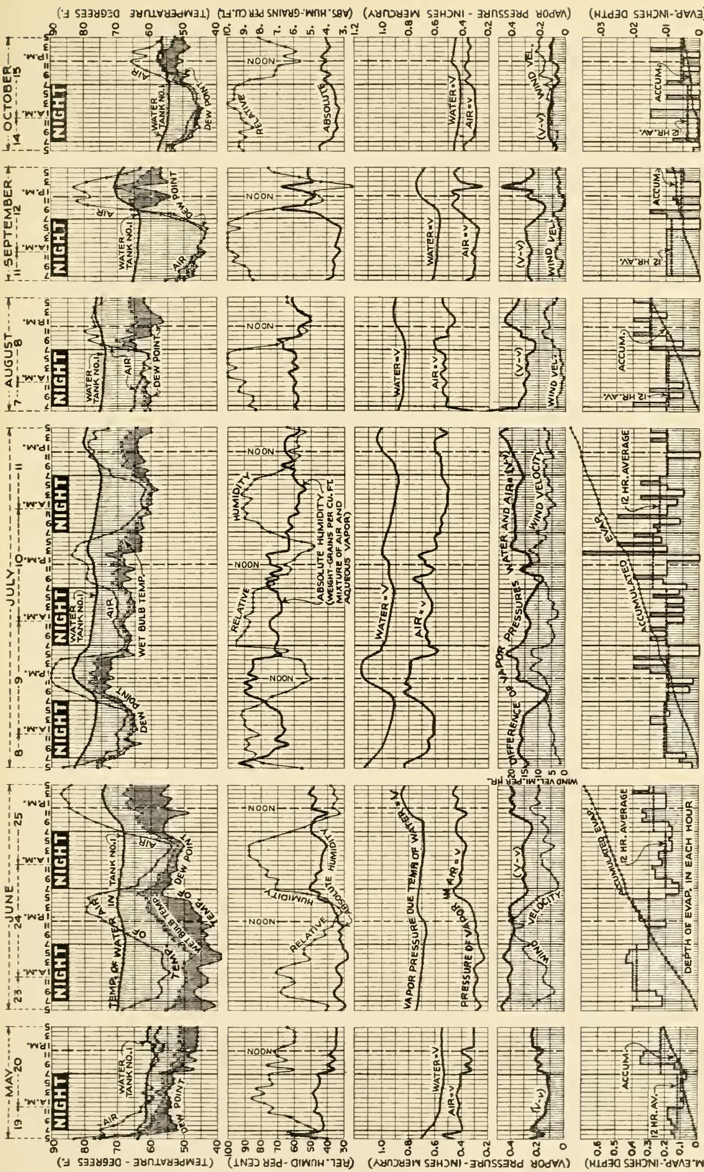
(g) And after all note the slight change in rate of evaporation shown by the apparatus.

(h) The equality of evaporation by night and by day.

(i) And that with a relative humidity of 90% the rate of evaporation measured by this apparatus showed little change.

Although Mr. Fitzgerald's autographic apparatus was uncommonly elaborate, apparently it lacked the extreme precision necessary to follow the changes in rate of evaporation from hour to hour, and the situation out of doors did not permit of separate measurement of the factors.

An average mid-summer evaporation of 6 inches per month, if at a uniform rate, takes 0.20 inch per day, or 0.008 inch per hour, and in mid-winter is less than 0.002 inch per hour, from all causes combined.



HOURLY VARIATIONS IN DATA OBSERVED
IN FITZGERALD'S EXPERIMENTS ON TANK NO. 1. FLOATING IN RESERVOIR.

Difficulties of Precise Measurement of Hourly Evaporation.

Explanation of the great scattering of data found in the observations of Fitzgerald, Bigelow and others, is found in the extreme difficulty involved in obtaining sufficient precision of measurement for accurately giving the depth evaporated from hour to hour, and also in the extremely variable character of the wind, during substantially all of these observations at data stations.

The relation (V-v) stands remarkably constant, more so than almost any other feature throughout these observations, and far more so than either temperature of air, relative humidity, or wind.

The great difficulty in the experiments on record, comes from a confusion of causes inseparable from the local conditions of the experiment, and from the extremely microscopic character of the changes in depth evaporated from hour to hour.

The apparatus for determining physical laws of evaporation and their constants and coefficients under out-of-door conditions, must measure with certainty the elevation of water surface from hour to hour, within 1/1000 inch.

In a floating tank of say three feet diameter and 3 feet depth (and to a greater extent in Mr. Fitzgerald's 10-foot tank) the cubical dilation of the water content, under its temperature change from hour to hour, combined with the linear expansion or warping of apparatus by temperature change, renders it practically impossible to measure the water levels much closer than to 1/100 of an inch in depth; and this makes the possible error of a single measurement, greater than the ordinary total evaporation during an hour in summer, or, perhaps greater than in 3 hours. Six inches per month is equivalent to an average depth of evaporation of only 1/120 inch per hour, and one inch per month to 1/720 inch per hour.

The wide fluctuations out-of-doors, in wind, temperature and humidity, are illustrated in the preceding diagram, which gives the data for representative observations by Mr. Fitzgerald on his 10-foot tank.

In none of the out-of-door experiments of Fitzgerald, or of Bigelow, or others, has it been found possible to separate the factors "C" and "K" relating to wind, temperature, and diffusion, so as to measure the effect of one at a time with satisfactory accuracy, therefore they have been combined in the formula $E = (V-v)(0.5+0.05W)$ devised by the present writer for estimating the depth of evaporation per 24 hours from the Great Lakes, or other lakes or reservoirs under similar climatic conditions.

After from one to five years of careful observation as described above, the general laws and methods for estimation of monthly depth of evaporation can be found out, and a simplified routine basis for observations established at the principal Weather Bureau Stations, which will cost very little of time or effort to maintain, and which, ultimately, will be of much value.

THE SUPPLY OF HEAT FOR EVAPORATION

A step by step review of the process of evaporation is helpful toward an appreciation of the influence of each of the several factors which determine the rate at which the transformation of water into vapor proceeds, and useful for exhibiting the great differences between the evaporation from these lakes and that from the experimental tanks, which one may expect to be caused by their different surroundings.

A much better insight can be had by making this analysis quanitative rather than qualitative.

It appears that the rate of evaporation must be controlled chiefly:

(1) By the rate of renewal of the films of air and water at the surface of contact.

(2) By the **rate at which heat can be supplied** to these contacting films, to replace the heat which is made latent and disappears in the process of vaporization.

In most discussions on rate of evaporation, strangely little attention has been given to the quantity, source, and rate of supply, of the heat required to produce a stated amount of evaporation.

Although the temperature-drop between the welt-bulb and the dry-bulb thermometers, measures the **loss in temperature** caused by evaporation, and the lessened temperature at the evaporating surface while the heat units for continued evaporation are being supplied from the air, **it does not measure the quantity of heat absorbed.**

Bigelow, and a few other physicists, have sought to make up formulas from the laws of thermodynamics and from the kinetic theory of the diffusion of gases into still air; apparently largely overlooking the important practical consideration that **still air is rarely found in nature;** and seldom or never is found over great lakes and reservoirs.

The motion of the motes in the beam of light from a projection lantern thrown across a dish from which water is evaporating in a room with closed windows and doors, will show plainly the turbulent motion nearly always present in air, and this constant movement of the air can be made still more plain with the aid of dense white fumes generated by the combined vapors from a few drops of strong aqua ammonia placed beside a few drops of hydrochloric acid in a shallow dish, near to the evaporating pan.

Somewhat as the quantity of steam per hour that can be generated from the water in an ordinary steam power boiler is limited by the rate at which heat units can be put into the water, so the rate of evaporation from an open surface of water at atmospheric temperature **is limited and controlled largely by the rate at which heat units per square foot of surface can be put into the films of water and air which are in contact;** and, so far as now known, this rate will be almost directly proportional to the velocity of the wind. The wind brings up a supply of heat in the fresh air, and also stirs up the water and from its depths brings up a supply of heat to help in replacing that absorbed.

For every pound of water evaporated at normal atmospheric pressure, about 970 thermal units, or Btu., must come from either the water or from the air to supply the latent heat of vaporization and expand this vapor.

Any prolonged chill near the surface of contact, due to abstracting this heat and due to lack of movement of the chilled and saturated air, **greatly slows down the process of evaporation.** The chilled air being heavier than the surrounding air does not rise readily from within even a shallow cavity below the rim and above the surface of water in an experimental evaporating pan.

By means of well established physical constants the writer has worked out some very interesting, step by step computations pertaining to the quantities of thermal units and the velocities of motion of vapor-laden air involved in the ordinary rates of evaporation and the velocity of the air currents required for the removal of the quantity of vapor formed under ordinary conditions, which show plainly that the **problem centers around the rate at which Btu. can be supplied at the surface of contact,** chiefly through the activities of the wind. It seems not worth while to now take space to print these computations. It will be more useful to report similar computations based on careful laboratory experiments, and to measure and trace the development step by step, from data measured in course of the experiments.

It becomes plain that while the actions and reactions involved are extremely complicated, **the complete action all revolves around a few facts, conditions, and quantities; each of which can be easily measured by ordinary instruments,** and the relation of which probably can be expressed simply according to the Dalton Law.

The line of laboratory experiment for determining the empirical laws and coefficients governing evaporation, one at a time, without confusion of causes, now seems so plain and relatively so simple, that the experimental method and empirical formulas obviously promise a more hopeful line of investigation for establishing the most practical form of equation than does a solely mathematical research.

It would seem that a brief and relatively inexpensive series of laboratory experiments with a small and inexpensive wind-tunnel properly devised, an electric fan, an electric water-heater, an electrically-driven water agitator, and a supply of ice, and ultimately a small refrigerating plant; with at least three electrical thermometers; one, half immersed within the surface of contact, and one about 0.10 inch above, and another 0.10 inch below the surface, would be extremely instructive, and would give these wind constants immediately and for all future time; presenting a formula of either the Dalton form (or perhaps of the Marvin form) in shape to be supplied with the additional coefficients next to be determined from precise observations in the open air, from a tank of generous size located preferably on an island or pier within one of the Great Lakes and provided with means for mechanical agitation, simulating the effect of the wind and waves, and permitting experiments with open water under zero air temperature.

If the Weather Bureau does not find it within its means to carry on such an investigation, it would make an admirable subject for a thesis for a doctor's degree at any one or more of the six or eight schools of science near the shores of the Great Lakes.

The writer believes it probable that by means of such experiments a simple formula embodying the Dalton Law and provided with experimental coefficients, could be developed which would meet all ordinary engineering needs, and would permit transforming with confidence, estimates from one set of climatic conditions to another.

NEW STUDIES ON THE PHYSICAL LAWS OF EVAPORATION AT THE CALIFORNIA INSTITUTE OF TECHNOLOGY

Since the above was in print the writer's attention has been called by Dr. Milliken to the researches in progress during the past year at Passedena, by Dr. I. S. Bowen and Mr. N. W. Cummings, thus far chiefly from the viewpoint of a laboratory problem in physics, but which will in the following months be carried forward and tried out by measurements on reservoirs and lakes.

This research treats the problem as one of measured insolation (or heat from sun and sky) by day and radiation at night, while taking due account of the thermal units going into and out from storage, and correcting for any loss by conduction at the sides or bed of the reservoir.

The two experimental tanks in the open campus have their side walls carefully insulated so that very nearly all heat transfer takes place at or through the water surfaces. Very curiously in the mathematical analysis the wind factor cancels out.

The writer has inspected the apparatus and conferred with Dr. Bowen and Mr. Cummings and believe these studies will prove of great value in advancing the understanding of the problems of evaporation in general and for southern California conditions, but he believes that the results will not be applicable to conditions on the Great Lakes for estimating monthly amounts because of ice and fog.

Also the writer has submitted these chapters on Evaporation to T. Howard Barnes, professor of physics at McGill University, a scientist who has conducted extensive researches on insolation and radiation upon lake and river surfaces. Dr. Barnes states that this large evaporation in winter from the Great Lakes and the small evaporation in May and June are of the order that his researches would lead him to expect.

SOME PREVIOUS ESTIMATES OF EVAPORATION FROM THE GREAT LAKES

Thomas Russell, U. S. Assistant Engineer, presents an approximate estimate on page 4122, Report of Chief of Engineers of the U. S. Army for 1904. This was made prior to the long succession of measurements of discharge of most of the important local tributaries of each lake, now available, and appears to have been guided largely by preconceived ideas of what should be expected. For example, the author says, regarding precipitation on the Lake Superior region, "For the winter period it is likely that very little of what falls on the land runs into the lake."

He deduces from his data upon depth of rainfall in connection with the discharge measured in the St. Marys River and the fall in the height of lake, that **if no water whatever ran off the land into the lake during the six months from September 1st to March 1st that the evaporation within this winter period of six months would be about 9 inches.** It is obvious that such a basis is surely too small, because of the well known winter discharge of rivers like the Nipigon, St. Louis and many others.

Mr. Russell's figures demonstrate that the **evaporation in these six months which include winter is surely greater than in the six months which include summer,** but he seems not to have appreciated this fact. His presentation is encumbered with needless algebraic formulas. The arithmetical computation without his formulas is extremely simple. In Lake Superior for example, using Mr. Russell's data on rainfall and discharge for the period of 16 years from 1883 to 1898, (first noting that 1.0 foot fall of surface is equivalent to an average outflow for six months at the rate of 56,250 cu. ft. per sec. and that the later surveys show that the drainage area of land is 1.54 times the area of water surface), is as follows:

For the winter six months, September 1 to March 1, using Mr. Russell's data:

	Depth on Lake Feet	Depth on Lake Inches
To the average rainfall from many stations around Lake Superior	0.88	10.6
Add the average fall of the lake surface during the period.......	1.09	13.1
Deduct for the average outflow from the lake, 70,250 c.f.s.......	1.22	14.7
Total average difference due evaporation **assuming no run-off from land into lake**..............................	0.75	9.0
The actual run-off from land into lake would increase this as shown by the stream gagings in recent years about..................		4.0
Making the winter evaporation about........................		13.0

Similarly using Mr. Russell's data for the six months, March 1 to September 1:

	Feet	Inches
To the Rainfall on the surface of the lake..................	1.31	15.7
Add 100 per cent. of the rain that falls on the land equivalent, in depth on the lake surface.............................	1.78	21.3
Deduct the average outflow from the lake, 69,540 c.f.s. equal to..	1.21	14.5
Deduct the average rise of the lake surface.................	1.09	13.1
Total average difference due summer evaporation **assuming 100 per cent of rain on land ran into lake** per Mr. Russell's hypothesis of 100 per cent run-off.........................	0.79	9.4
The actual loss in transit, of the summer rainfall upon the land before it reached the lake, as determined from recent gagings of many streams would lessen this by about................		8.0
Making the evaporation for the six summer months equal to only about..		1.5

Following Mr. Russell's method **but using wholly recent data** covering the 4 years of low water, 1921 to 1924, instead of the 16 years, 1883–1898, we obtain the following:

For the winter period, September 1 to March 1.

	Depth on Lake Feet	Depth on Lake Inches
If there had been no run-off from the land,		
To the average rainfall on the lake surface, 11.51 inches........	0.96	11.5
Add the average fall of the lake surface......................	0.89	10.7

	Depth on Lake Feet	Inches
Deduct for the average outflow from the lake, corrected for ice, 48,280 c.f.s.	0.86	10.30
Total average difference due winter evaporation **assuming no run-off from the land**	0.99	1.19
Meanwhile, the stream flow into Lake Superior shown by the many gagings by the U. S. Geol. Survey and the Canadian Water Resources Branch has averaged		4.40
Therefore, this gives as a measure of the actual evaporation in the six winter months		16.30
For the summer period, March 1 to September 1.		
If all the rain that fell on the land had run into the lake,		
To the average rainfall on the lake surface	1.25	15.01
Add the average run-off, equivalent depth on lake surface	1.92	23.11
Deduct the average rise of the lake surface	0.70	8.40
Deduct for the average outflow from the lake, corrected for ice, 49,020 c.f.s.	0.87	10.42
Total average difference due summer evaporation **Assuming 100 per cent of rain on land ran into lake,**	1.60	19.30
Allowing for the actual loss in transit shown by the recent gagings or difference between rainfall and run-off	0.90	10.80
We find the evaporation thus measured for the six summer months	0.58	6.90
Giving a total average yearly evaporation for the 4 years 1921–1924 equal to	1.94	23.21

According to the stream gagings, the run-off from the land during the six winter months was 25% of the rainfall; and during the six summer months, was 47% of the rainfall.

Mr. E. S. Wheeler, U. S. Assistant Engineer presents estimates for evaporation losses in **inches depth from the entire area of combined land and lake surface, without separation,** in the Report of the Chief of the U. S. Army Engineers for year ending June 30, 1903.

He makes no separation into months or seasons and no distinction between summer and winter evaporations. His computation finds the difference between the total precipitation in rain and snow for many years and the measured discharge from each lake as gaged in the St. Marys, St. Clair, Niagara and St. Lawrence rivers and after correcting for rise or fall of lake within this period, spreads the difference **over the entire drainage area, land and water,** and finds values as given in the last column of the following table:

The corresponding estimates by J. R. Freeman are presented for convenient comparison.

EVAPORATION FROM ENTIRE DRAINAGE (LAND AND WATER) OF EACH LAKE, 1860–1924

Lake	Average Yearly Rainfall (J. R. F.) Inches	Average yearly outflow c. f. s.	Average yearly outflow Equivalent Depth On Whole Drainage Area Inches	Evaporation Deduced by J. R. F. From Whole Drainage Area 1860–1924 Inches	Evaporation as Deduced by E. S. Wheeler For Years 1882–1898 Inches
Superior	27.9	76,020	10.66	17.24	13.75
Huron-Michigan	32.1	105,380	8.41	23.69	20.56
Erie-St. Clair	34.4	26,500	7.30	27.10	26.10
Ontario	33.4	24,340	7.95	25.45	23.82

NOTES ON EVAPORATION BY D. FARRAND HENRY, U. S. ASSISTANT ENGINEER

In the reports of the U. S. Secretary of War, 1867 to 1870, are presented meteorological reports in great detail, prepared by the U. S. Lake Survey, which include observations upon evaporation at 8 stations on the U. S. side of the Great Lakes:

1. Superior, Wis.
2. Ontonagon, Mich.
3. Milwaukee, Wis.
4. Tawas, Mich.
5. Thunder Bay Island, Mich.
6. Detroit, Mich.
7. Monroe, Mich.
8. Cleveland, Ohio

These observations of evaporation cannot be accepted as representing that from the Great Lakes, for reasons stated below.

The observations for non-freezing weather were made in an evaporimeter consisting of a small zinc basin with vertical sides, on top of a building, exposing a water surface equivalent to 10 inches square; the depth of water in which was measured by a micrometer screw at the side.

In the Report of 1868–69, page 978, Mr. D. Farrand Henry says:

> "The evaporators used are generally placed on top of the meteorological house, or in some place near, where fully exposed to the sun. The temperatures in them are therefore much greater than that of the lake and the evaporation proportionally larger. I, last year, attempted to make comparisons between an evaporator in the usual position and one in the water. Unavoidable accidents prevented many observations being made, but the results obtained show that lake evaporation is not over 64 per cent of that shown by the instrument on land close-up."

In Report 1869–70, page 645, Mr. Henry states:

> "From the few observations made in 1867 I estimated the evaporation from the lake surface to be 64 per cent of that recorded by the evaporators. The more extended observations made this year show that estimate was too large."

He then proceeds to recompute the values for each month at each of the eight localities previously given; **using 50 per cent of the observed evaporation,** during the six months from May to October, using this same percentage for all times and stations. No **consideration was given to the lower temperature of the mid-lake surface,** or to relative exposure of surfaces to the wind.

For the freezing months the estimates were mainly guess work, as will appear from the following notes: His basis for estimating evaporation in freezing weather is described in Report for 1868–69 on page 977. He first found the relation between evaporation and the temperature of air during the non-freezing months by various observations at Milwaukee, from 1861 to 1866, which showed during November a daily average evaporation in inches depth equal to about 1/1000 part of the reading of the thermometer in degrees Farenheit, but in April he found this proportion about three times as great, and therefore concluded:

> "Now the evaporation in this climate in winter must be very small, much smaller than in November, but as it rises so rapidly in April it is probable that the evaporation in March is comparatively large, so if we take 1/1000 of the temperature as the evaporation for the winter months we cannot be far from the actual amount."

Thus he makes plain that his estimates of winter evaporation rest on an assumption tempered by a preconceived notion that "the evaporation in winter must be very small."

Nevertheless he works out a record of evaporation for each of his eight stations around the Great Lakes for the six years 1862 to 1867 inclusive to decimals of a thousandth of an inch, month by month.

His rainfall data of these early years (60 years ago) are of interest for comparison with those from the far more complete data accumulated during the past half-century, and therefore are presented below alongside his figures for evaporation. Both are taken from page 648, Table VII, Report 1869–70, and extended to a yearly basis instead of an average daily basis.

Name of Lake	Mr. Henry's Estimates	J. R. Freeman's Estimates	Mr. Henry's Estimates	J. R. Freeman's Estimates
	Average Total Annual Rainfall Inches	Average Total Annual Rainfall Inches	Average Total Annual Evaporation Inches	Average Total Annual Evaporation Inches
Superior	28.1	27.9	12.05	22.0
Michigan	30.6	32.1	17.5	27.5
Erie	32.6	34.4	18.6	36.0
Huron	27.9	32.1	18.2	27.5
Ontario	32.6	33.4	17.9	33.0

In fairness to Mr. Henry it should be said that he used the best information that he had at hand and that his frankness of description was plainly intended as a warning. Nevertheless his figures on evaporation have sometimes been published without this warning as to their **doubtful basis in summer, their guesswork in winter, or their lack of relation to actual temperature of the mid-lake surface.**

Aside from these estimates of evaporation and the uncertainty of vapor pressure observations in freezing weather to which he calls attention, his remarkably complete tables of data on air temperature, rainfall, humidity, barometer, wind velocity and wind direction and cloudiness, are all of great value.

APPENDIX NO. 3

CAUSE OF THE APPARENT LOWERING OF LAKE HURON RELATIVE TO LAKE ERIE

The question of just how much the lowering of the levels of Lakes Huron and Michigan has been for a stated rate of discharge, and how this lowering was caused, have been much discussed and disputed for 25 years past, and both are of much importance, for two reasons.

1. It is important to find out if the formulas, derived by the current meter measurements in 1888 to 1901, in the St. Clair River for estimating the discharge, can be used in all previous years, back to 1860 and beyond, because the discharge of Lake Huron, year by year, has to be estimated from the records of the observed height of Lake Huron, in connection with the height of Lake St. Clair.

2. It is important to learn the truth about the statement that the work done by government agencies in dredging channels between Lake Huron and Lake Erie has lowered Lakes Huron and Michigan by a greater amount than the lowering of the lakes caused by the diversion through the Chicago Canal. If this is true, it is obvious that the entire burden of providing a remedy should not fall on Chicago.

The weight of the best and most recent evidence, indicates that the total lowering caused by dredging does not, at most, exceed 3 or 4 inches and was mostly caused 30 years or more ago.

It is the opinion of the writer of this report that this lowering of Lake Huron is more apparent than real, and that the chief cause of this apparent lowering has been the earth-tilt, described in a preceding chapter.

A review of the data, also a review of various expert opinions regarding the amount and the causes of the change, is presented on the pages which follow.

A Brief History of the Discussion

The questions of amount and cause of this lowering of Lakes Huron and Michigan were first brought conspicuously into notice by the report of the Board of Engineers on Deep Waterways, published in 1900, just prior to the opening of the Chicago Canal, which states, on page 83:

> "The mean level of Lake Huron is apparently about one foot lower than it was 15 years ago, which change has resulted from the enlargement and deepening of channels for waterway improvements and from the natural erosion of the bed of the river at the outlet of the lake. This change of stage in Lakes Huron and Michigan has produced a like effect in the depth of channel through the St. Mary's River below the St. Mary's Rapids."

That there has been a change in the average fall from Huron to Erie as measured between the standard water stage gages at Harbor Beach and Cleveland, amounting to nearly a foot, is easily seen by close inspection of the frequently published diagram of average monthly levels of the Great Lakes, year by year, since 1860, (see page 198A), and is brought out with particular clearness by the diagram on a following page (513).

It seems plain that Huron must have become lower, or Erie higher.

All present lines of evidence from comparison of the water gages at Harbor Beach and Cleveland, point toward Huron as having become lower than in the earlier years for the same rate of discharge.

This same diagram also shows that prior to 1890 Lake St. Clair generally stood higher in relation to Lake Erie than since that time.

Earth-tilt has raised the outlets of all of the Great Lakes by varying amounts.

None of the facts in hand (except earth-tilt) show any reason why Lake Erie should, in recent years, average materially higher for a stated average rate of discharge in cubic feet per second, than it stood from 30 years to 70 years ago.

Reasons for believing that Erie has not become higher are:

(1) The gage by which the elevation of Lake Erie has been measured at Buffalo since 1887, or for 38 years past, is near to the outlet section controlling its discharge.

(2) The outflow from Lake Erie is over a broad flat limestone ledge where no obstructing sand bars form, as they do near the outlet of Lake Huron, and

(3) No important obstructions have been built in the Niagara River, sufficient to restrict its discharge, or to cause Lake Erie to stand higher.

The piers on the International railroad bridge, across Niagara River, stand 2.6 miles downstream from the head of the rapids, where the surface of the water has fallen about 5.4 feet from the level of Lake Erie, and any possible rise in Lake Erie that obstruction by these piers could cause, added to that caused by the projection of the water works pier into the channel, is less than the lowering of Lake Erie of about 4.2 inches caused by the increased diversions for power taken out a short distance upstream from Niagara Falls, and through the Welland Canal.

Today, we have 25 years more of accurate observations than were available to the Board of Engineers on Deep Waterways, but nevertheless, a precise answer to these questions is still obscure until the effect of earth-tilt is invoked, because of the complication of climatic with hydraulic conditions.

All of the Great Lakes have fallen to a most remarkable extent since 1890. About 1886 came the culminaton of a cycle of high lake levels, and during the entire period of careful observation of lake heights, or within the past 70 years as a whole, a remarkable lessening of water yield has been going on. (See page 514.)

Today, the government engineers in charge of the surveys of channels and harbor improvements of the Great Lakes, appear strongly of the opinion that the engineers of the Board of Deep Waterways were mistaken in this particular estimate and that the permanent lowering of Huron and Michigan relative to Erie, has not been so great as the one foot stated by the Deep Waterways report, and that the portion of the total lowering which has been caused by artificial deepening of channels is not more than from 2½ to 4 inches, and that the lowering due to this cause all happened more than 25 years ago. Also this belief in a smaller change and a different cause is shared by skillful observers like Sabin, Shenehon and Richmond, who have been in close contact with these gagings for many years.

The experts called by the City of Chicago in the ligitation of 1913 about the allowable extent of Chicago's diversion, held largely to this opinion published by the Board on Deep Waterways, in 1900, that the actual lowering had been about 10 or 12 inches, and it seems worth while to review the opinions that have been strongly maintained on both sides, in the light of the evidence of more recent gagings, and of this study of earth-tilt, for the two important reasons stated above, also because;

(3) This study may throw some light on the relative accuracy of the discordant estimates of discharge from year to year of the St. Clair, Detroit, and Niagara Rivers.

(4) This study may give data upon the extent to which Lake Huron can be caused to rise by raising the level of Lake Erie, and

(5) Because with the new data on earth-tilt, the time now seems to have come for reaching definite conclusions and ending this long continued controversy.

The Deep Waterways Report on Cause of Change

On page 280 of the Deep Waterways Report of 1900 it is stated:*

"Previous to 1886 the average fall from Lake Huron to Lake Erie was 9.2 feet, after which date the slope gradually diminished until 1890, since which time it has had an average of 8.3 feet. **This decrease of slope was caused by the deepening of the river channels at the St. Clair Flats and at the Limekiln Crossing by the Government, and by the great increase from natural causes in depth and cross-section of the St. Clair River through the rapids at the outlet of Lake Huron.**

"A survey made at the request of this Board in December, 1898, by a party under the direction of Lieut.-Col. G. J. Lydecker, Corps of Engineers, U. S. Army, shows that the gorge at the head of the river now has a central depth of 66 feet and a cross-section of 36,000 sq. ft., whereas at the date of the previous survey, in 1867, the central depth was only 48 feet and the cross-section 30,000 sq. ft.

"While there are no records that show when the deepening of the channel through the Rapids occurred, a study of the water levels and slope curves shown on plate 83 indicates that **the erosion was probably started in the spring of 1886 by the abnormal fall (7.5 ft.) of the St. Clair River at that time.**

Abnormally large fall in either the St. Clair or Detroit Rivers indicates the presence of an ice gorge, which may plow up the soft bottom, after which the swifter current beneath the gorge and the abnormally high velocity after the gorge has disappeared, both may promote scour of the river bed, where thus plowed.

* Bold face type are not used in the original publication. They have been added by the present author to more clearly bring out the matters now in question.

The Board on Deep Waterways says, further:

"To determine what the effect of change of stage in Lakes Huron and Erie has been upon the slopes of the connecting waterway, a line of precise levels was run, under the direction of this Board from Lake Erie to Lake Huron,* and connections made with 15 different gauges at critical points of the rivers, which were read simutaneously for a week at two different periods, when the stage of the lakes had a difference of 0.66 feet.

"The profiles of these slopes are shown on Plate 82, (of Deep Waterways Report of 1900), which, in connection with the curve of monthly mean slopes of the Detroit and St. Clair Rivers from 1873 to 1898, shown on Plate 83, indicate that **if the low-water stage of Lake Erie be raised and maintained 3 feet above its natural elevation the corresponding low-water stage of Lake St. Clair would be raised 2 feet and Lake Huron 1 foot, making the resulting low stage of Lakes Huron and Michigan approximately what it was before being lowered by the deepening of the river channels."**

It appears to be in accordance with the views thus expressed by the Board, for us now to assume that the high level (574.7) at which the Deep Waterways Board proposed to maintain Lake Erie by the dam which they recommended at the head of the Niagara River, in addition to other purposes, was designed for the following purposes:

(1) To restore to their normal height, the depths in channels between Lakes Erie and Huron, and also,

(2) To restore the levels of Lakes Michigan and Huron, and also,

(3) To restore the depth in the St. Marys channel, below the locks, prior to being thus lowered by the deepening of the Huron outlet.

(4) Also, this proposed high level for Erie, probably anticipated compensation for whatever lowering might be caused by the diversion of 4,167 cubic feet per second of water through the Chicago Sanitary Canal, then under construction but not yet opened.

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*Note—The re-running of this line of precise levels now, after the lapse of 27 years and for a distance of about 80 miles, might give valuable independent evidence upon earth tilt in this locality, although the difference to be expected is only about

$$\frac{80}{100}\text{ (miles) x }\frac{27}{100}\text{ (years) x 0.6 ft.} = 0.13\text{ ft.}$$

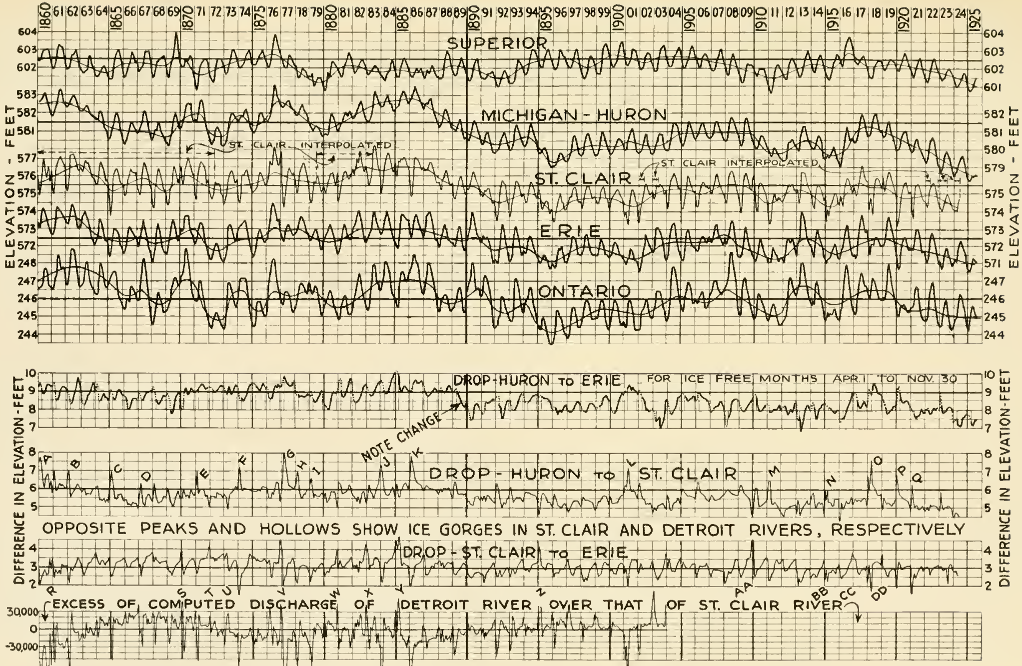
or scarcely outside the limits of probable error.

This apparent erosion in the gorge at the head of St. Clair River, reported by the Board on Deep Waterways, is found described in the earlier report of the Chief of U. S. Army Engineers for 1899, page 3,854, and so far as erosion of channel bed **in the gorge at the head of St. Clair River** was concerned as a cause, both reports were based on the same data.

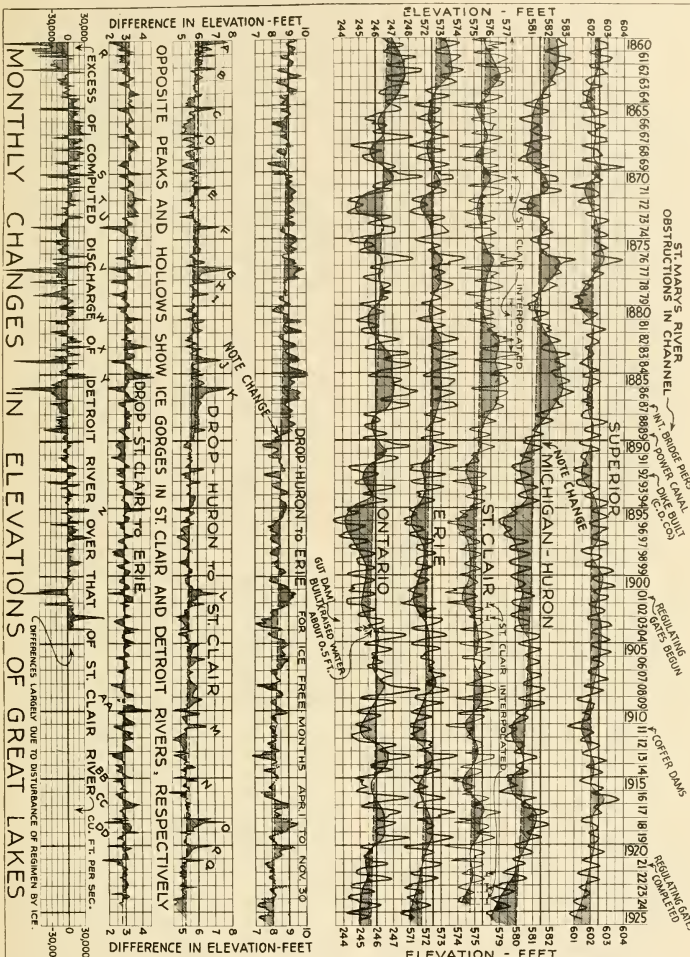
The two full page diagrams which follow, present in condensed form a comparison of the average height of each lake, month by month, for the past 65 years. The first is made up from the folding diagram on page 198A, with the addition at the bottom of a series of comparisons of the drop between Huron and Erie, Huron and St. Clair, and St. Clair and Erie.

The bottom diagram compares, month by month, the discharge of the St. Clair and Detroit Rivers. Each as estimated by formulas or diagrams derived from current meter gagings, with simultaneous elevations in the adjacent lakes. Differences in these estimates of discharge are caused chiefly by the effects of ice obstructions in either or both the St. Clair and Detroit Rivers.

The second full-page diagram is substantially the same as the first, except that the probable effect of earth-tilt has been shown superimposed.



MONTHLY CHANGES IN ELEVATIONS OF GREAT LAKES



GENERAL TREND OF LAKE LEVELS DUE TO CLIMATIC EFFECTS SHOWN AFTER CORRECTION FOR EARTH TILT AND DIVERSIONS.

	LOCATION OF GAGE	DISTANCE FROM AXIS	PROBABLE EARTH TILT PER 100 MLS. PER 100 YRS.	DROP SHOWN PER GAGE IN 65 YEARS	PROBABLE GAGE CORRECTION FOR TILT	PROBABLE TOTAL NET LOWERING	LOWERING BY CANAL DIVERSIONS	CORRECTED LOWERING IN 65 YRS. WITH NO DIVERSIONS	
SUPERIOR	MARQUETTE	50 MLS.	1.00 ± FT.	0.25 FT.	−0.32 ± FT.	−0.07 ± FT.	0	−0.07 ± FT.	NOTE OBSTRUCTIONS IN CHANNEL SINCE 1887.
MICH.-HURON	MILWAUKEE	90 "	0.63 ± "	1.75 "	−0.37 ± "	1.38 ± "	0.47 FT.	+0.91 ± "	POSSIBLY AFFECTED BY CHANGES IN CHANNEL AREA SINCE ABOUT 1890.
ST. CLAIR	FLATS CANAL	150 "?	0.63 ± "	1.00 "	−0.61 ± "?	0.39 ± "?	0.50 "	−0.11 ± "	GAGE INTERMITTENT. THIS FIGURE FOR TILT ASSUMES CONTROL FROM OUTLET OF LAKE ERIE.
ERIE	CLEVELAND	172 "	0.63 ± "	1.00 "	−0.70 ± "	0.30 ± "	0.76 "	−0.46 ± "	DISCHARGE OVER LEDGE WITH SMALL CHANGE.
ONTARIO	OSWEGO	110 "	1.44 ± "	1.00 "	−1.03 ± "	−0.03 ± "	0.42 "	−0.45 ± "	DISCH. OVER LEDGE WITH SMALL CHANGE EXCEPT GUT DAM WHICH RAISED WATER ABOUT 0.50 FT.
			1.00 ± "	1.00 "	−0.65 ± "	−0.35 ± "		−0.07 ± "	SAME, WITH TILT AT 1.00 INSTEAD OF 1.44.
			1.44 ± "	1.50 "	−1.03 ± "	−0.47 ± "		+0.05 ± "	SAME, WITH TILT AT 1.44 AND ALLOWING FOR 0.50 FT. RISE DUE GUT DAM.

A New Review of Data on Fall Between Lakes

A new review of the old data, made by the present writer with the aid of the observations of the past 25 years, indicates that the fact that in 1900 Lake Huron appeared about one foot lower than it was 15 years previously, as quoted above from the report of the Board of Deep Waterways, **was mainly due to a sudden diminution in the water yield of all of the lakes, apparently caused by a change in climatic conditions.**

Lake Superior dropped but slightly from 1890 to 1894, and for the next 10 years averaged nearly half a foot higher than in the 10 years prior to 1890, while Michigan-Huron stood from 1.5 ft. to 2.5 ft. lower. Ontario dropped about 1.5 ft. simultaneously with Huron; and meanwhile Lake Erie, which is relied upon as the most accurate gage for measuring the water yield of all of the lakes, dropped suddenly about 0.7 ft. in elevation, which corresponds to about 15,400 c.f.s. less discharge in the Niagara River. Less head was required to take the lessened discharge from Lake Huron over the long line of "submerged weirs" near Lake St. Clair, which largely controlled the outflow.

Nevertheless, the fact that the outlets of Lake Huron and Lake Erie, as shown in their discharge diagrams on page 212, have almost precisely the same increment, such that 22,000 c.f.s. diminution of discharge causes a drop of almost precisely one foot in each lake, would lead one to expect that **Lake Huron would drop no more than Lake Erie, unless there was some new factor introduced.**

One naturally looks first for this new cause in a deepening of channels, because it is a matter of common sense to expect the surface of a basin of water to drain down when its outlet is deepened.

In any precise studies of cause of change in fall from Huron to Erie one must consider separately:

(1) Changes at the narrow gorge found at the outlet of Lake Huron, which has a steep fall of water surface.

(2) Changes in obstruction to flow in the shallow channels of the St. Clair Delta, which virtually form the crest of the upper series of "submerged weirs" that hold back the discharge.

(3) The effect of the changes made over the shoals of the Detroit River, at Limekiln crossing.

(4) Effect of the new Livingstone Channel.

The shallows at the Limekiln crossing and along the Livingstone cut, form the lower series of "submerged weirs" which help to hold back the discharge from Lake St. Clair.

(5) The different effects of ice in different winters, in obstructing the discharge and raising the level of Lake Huron by a greater amount than the level of Lake Erie is raised by ice. The discharge from Huron is nearly always held back far more by ice gorges, than is the discharge from Erie.

(6) Changes in the average rate of discharge, or water-yield of the Lakes up stream from the St. Clair and Niagara Rivers in the two periods, before and after the observed change in drop.

(7) **A slow tilting of the surface of the earth,** upward toward the north-east, at the rate of somewhere about 0.5 ft. to 0.8 ft. per 100 miles per century, about which more is said later.

Relations of Lake Levels, Etc., to Drop Between Lakes

The diagram on page 491 has been prepared to bring into one view;

(1) The monthly average lake levels and the drops between Huron, St. Clair, and Erie.

(2) The opposing peaks and hollows in the lines of comparisons, which suggest ice gorges in the St. Clair or Detroit Rivers.

(3) The excess of computed discharge in the Detroit River, over that of the St. Clair River from year to year, which, prior to any adjustments for ice effect, also indicates the presence of ice by its abnormal differences.

This diagram in its lower half, indicates that from year to year **the effect of ice gorges is the greatest of all disturbing causes in changing the fall** between lakes Huron and Erie from year to year.

The peaks, B, C, D and E, etc, in the diagrams are all found to come during the ice season. If the gorge is in the St. Clair River, the drop from Huron to St. Clair becomes largely increased; while on the other hand, if the gorge is in the Detroit River and the St. Clair remains relatively ice-free, the drop between St. Clair and Erie will become largely increased, and that from Huron to St. Clair decreased.

It will be noted in comparing these three lower diagrams that the peaks and hollows occur simultaneously in opposite directions and that they all are in the ice season.

The lowest diagram on page 491 shows the excess of the computed discharge of the Detroit River over that of the St. Clair River, as worked out by Engineer Russell, and reported in the tables to be found in Chief of Engineers Report for 1904, pages 4096 to 4105, which at times indicates 40,000 second feet excess, and sometimes more than 50,000 second feet deficiency, and **illustrates the very large error that may be introduced by lack of definite knowledge of the amount and duration of the ice obstruction year by year.** In fact, this diagram gives the best indicator of any which we possess, as to when severe ice gorges have occurred, altho it is not always a safe measure of the decrease in cubic feet per second flowing, because the relative amount of obstruction in each of these two rivers is not known.

Each period of wide divergence indicates plainly a period of severe ice obstruction. Because these appeared to have been more frequent prior to 1890, or 1900, than subsequent thereto, Mr. Sabin concluded that the change in fall from Huron to Erie may have been in part caused by a change in the frequency or duration of ice obstruction, before and after the critical time.

The upper Niagara River is much less affected by these vagaries of ice obstruction than is the St. Clair River. This is fortunate because the upper Niagara River serves as our measuring place for the discharge of the Great Lakes system throughout this period of 60 years, and from its indications we have to build up our mass curve, and work out the gain to be had from a larger minimum discharge and increased amount of "firm" power.

A Remarkable Change in Water Yield

A general change appears to have occurred between the years 1885 and 1896, such that after this change all of the lakes (except Superior) stood at lower average elevations, which indicates a smaller water yield than before. This fact stands out strongly in the diagrams of lake elevations at the top of page 492. Michigan-Huron shows the greatest change on the diagram of heights, but the change in the yield of Ontario is similar, and Erie, plainly, is similarly affected.

The change in height and discharge of Erie is brought out clearly in the diagram at the bottom of page 514.

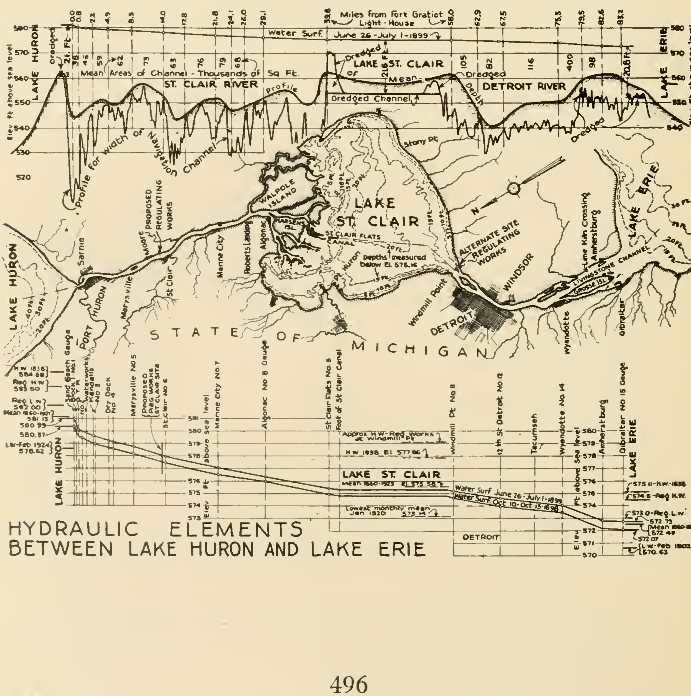
The drop from Huron to Erie, being analagous to the effective total head which causes discharge over deeply submerged weirs, was made smaller by reason of the smaller quantity to be discharged over the weir.

The statements of the preceding pages will indicate that it is difficult to separate out and sub-divide the causes of this evident change in fall from Huron to Erie which, from comparing the water-stage gages at Harbor Beach and Cleveland (without reference to earth-tilt), seems to have been about 0.80 foot.

A study of the profile on the map below shows that the flow between Huron, St. Clair and Erie may be regarded as in large part controlled by a complicated system of irregular submerged weirs, located a long way apart, near the middle and lower portions of a channel about 80 miles in length.

It is obvious that trimming a few feet off the crest of a weir affects the discharge more than a change in depth of the deeper channel between the weirs, and the diagram on page 33 shows that in general 1 ft. increase of backwater from Lake Erie retards the discharge over this submerged weir no more than a decrease of 0.17 part of this amount in the upstream head.

In the following diagrammatic representation of the profile of these rivers, note that **the surface of the downstream pool is far higher than the crests of the "weirs,"** and that the total effective head, or amount of drop over each weir, is very small in proportion to the depth of submergence of the crests.



HYDRAULIC ELEMENTS
BETWEEN LAKE HURON AND LAKE ERIE

The profile alone fails to tell the whole story, but needs to be studied in connection with the chart, because of the great width of some of the shoals, particularly those at the outlet of Lake Huron and at the inlet to Lake Erie. Nevertheless, **depth is a powerful factor,** as well as is area of cross section, and **the current mostly follows the deep channel.**

Plainly, the discharge from Lake Huron is controlled chiefly by the elevation of Lake Huron, and in only a minor degree by the height in Lake Erie.

Until the current-meter gagings of 1889 to 1902 were well advanced, it appears to have been thought that the narrow gorge, 2 or 3 miles in length, at the head of the St. Clair River, within which there is a drop of from 2 to 3 feet, controlled the discharge; because, at first, it was sought to measure the rate of outflow from month to month, solely in terms of the elevation of Lake Huron; but later it was found that a more accurate measurement could be had by also including the simultaneous elevation of Lake St. Clair as an important factor.

A formula for the discharge of the Detroit River, in terms of the elevations of Lakes St. Clair and Erie was developed as a check and for use when the St. Clair River was obstructed by ice and the St. Clair formula thereby rendered unreliable.

The present writer is inclined to believe, after a study of the form of the "Submerged Weir" in its relation to the levels of the three lakes, that a more accurate discharge formula could have been worked out for giving average discharge during ice-free conditions by making the discharge a function of the elevation in Huron and that in Erie, rather than of Huron and St. Clair; but he has not taken the time to try to work this out in detail.

A discharge diagram for Lake Huron based on the total fall to Lake Erie, is given on page 33.

Now, since earth-tilt has been brought into this question, it is plain that the two standard gages for measuring this fall should have been close to the outlet of Huron and close to the inlet to Erie, respectively.

ADDITIONAL EXPERT STUDIES AND CONCLUSIONS

The strong statements above quoted, from such eminent engineers as constituted the Deep Waterways Board and its staff, naturally promoted further investigations of the cause and amount of the change in elevation in Lakes Huron and Michigan and their connecting channels. Promptly, a re-survey was made of the cross-sections apparently chiefly controlling the discharge from Huron, found in the deep narrow gorge at the head of the St. Clair River. The U. S. Chief of Engineers Report for 1900, page 5,320, gives the following statement, by Col. Lydecker, District Engineer, of one result of this re-survey;

> "In my last Annual Report (page 3,854 Ch. of Engineers 1899), I stated that we had found indications of a marked deepening since 1867, in the channel of the St. Clair River just below its head, and it was thought this might have caused a material change in the outflow from Lake Huron in recent years; but **further careful investigation shows that there has been no such change in the regimen of the river."**

Also, Assistant Engineer E. E. Haskell states on page 5,323, Chief of Engineers Report 1900; relative to change of depth within the gorge;

> "In my last year's report I called attention to what at that time seemed a clear case of enlargement, by scour, of the head of the St. Clair River. A preliminary survey of this reach was made by Mr. Sabin in December, 1898. The results of this survey when compared with the chart of the survey of 1867, showed what seemed to be a cutting out of the river bed to a depth about 18 feet greater, for an area covering a portion of the gorged reach. Upon the strength of this evidence I made the statements which appears in my last Annual Report. Early last fall Mr. Sabin called my attention to the fact that the survey of 1859 of this reach, as chartered, agreed much closer with present conditions than did the survey of 1867."

The original survey notes of 1867 were meanwhile replotted on a larger scale, putting on all of the soundings, some of which had been omitted on the former chart because of its small scale.

Mr. L. C. Sabin describes (page 5,362, Chief of Engineers Report 1900) this new survey of the head of the St. Clair River, which was made in great detail, preliminary to an extension and elaboration of previous measurements of discharge by current meters, for discovering causes of discordant results and on page 5,395 he states his conclusion about change of cross-section in the gorge at the head of the St. Clair River, but makes no comment on the effect of the deepening at the St. Clair Flats and at the Limekiln Crossing mentioned by the Board as also a cause, except a statement on page 5,398, that **about 0.2 ft. of the lessened fall could be accounted for by changes made in the lower river.** He says:

> "The soundings shown on the map of 1859 are apparently accurately located and agree very closely with the results of our recent survey," (1898). "The survey of 1867 is by no means as satisfactory."

He found that the survey notes of 1867 could be interpreted so as to give horizontal contours of depth, within the upper few miles of the St. Clair River, that agreed tolerably with recent surveys. The sounding intervals along station lines surveyed in 1867 apparently had been spaced by speed of the boat and not by precise instrumental location of the spot where each depth was measured.

He found the minimum cross-section at the head of the river (Section No. 4) at 3,200 ft. below Fort Gratiot, was in 1899 about 35,000 sq. ft. in area, which is in close agreement with the 36,000 sq. ft. found in December, 1898, reported by the Board, and shows enlargement from the area 30,000 sq. ft. found in 1867, mentioned by the Board. On page 5,396, he concludes that between 1859 and 1867 the area in the most restricted section may have increased 9,000 sq. ft. for a length of about 600 feet. In other words, **the time of this erosion and enlargement of the relatively short narrow gorge** at the outlet of Lake Huron was thereby **put much farther back than the spring of 1886,** which was suggested as the date of its occurrence, by the Board of Deep Waterways in the quotation above.

It should be noticed that this re-survey, reported in 1900, pertained only to the deep narrow gorge a few miles in length at the head of the river, **within which space there had been no dredging;** and that the discrepancy, discussed above by Mr. Sabin, related only to the position of depth contours within this short and narrow gorge.

In other words, this investigation by Engineer Sabin, of the change reported in 1900 by the Board on Deep Waterways, appears incomplete and it seems that no particular investigation was made of effects or of possible changes near Lake St. Clair, because of the belief then held, that the rate of discharge from Huron was controlled chiefly by conditions near the head of the St. Clair River.

Mr. Sabin concluded from his elaborate comparison of slopes and depths between Lakes Huron, St. Clair and Erie, that while his more recent surveys showed no important change of hydraulic conditions of the river bed in the first five miles of this 80-mile channel, **the records**

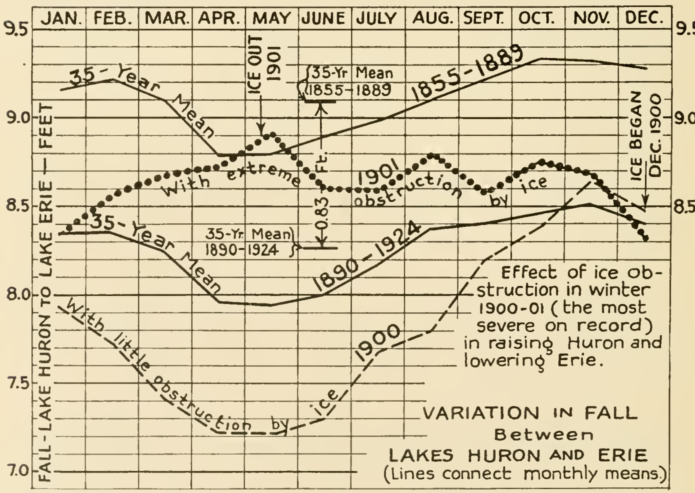
of lake elevations showed that for the preceding 10 years—1890 to 1900—the average elevation of Lake Huron had been about 1.70 feet below its average for the preceding 34 years.

Mr. Sabin concluded, as already stated, that possibly the improvements in the Detroit River might account for 0.2 foot of this reduced fall, and sought explanation for the remainder in climatic conditions, and thought that the **holding back of the Huron discharge** by **ice in the early years might have been an important contributing cause.**

Regarding this retardation by ice he said:

> "Nature has provided a system of regulating works in the St. Clair River which she has neglected to use to their full capacity in recent years."

Mr. Sabin presents in the Chief of Engineers Report for 1902, page 2,779, an extremely interesting diagram, re-produced below with additional lines prepared in the further study of retardation by ice,



which shows, particularly, the effect produced in the remarkably severe ice conditions early in 1901, which were the most severe on record up to that time. The flow of the St. Clair River was at one time, in 1901, found so obstructed by ice that only 65,000 c.f.s. was left flowing, as measured by current meter, **which was only one-third of the normal flow.**

The diagram on page 36 gives another illustration of the severe holding back of discharge caused by ice in winters of exceptional severity.

Although three months of ice obstruction like that of 1901, by holding back the discharge through St. Clair or Detroit River, can raise Lake Huron 0.16 feet within one month, or 0.53 ft. in the course of the one winter as is readily computed from dividing the quantity held back during a known period of time, over the known area of the lakes, it will require several years to drain it down an equal amount. See note about slow readjustment in lowering, on page 218.

The diagram on the preceding page shows how severely Lake Erie falls while Lake Huron rises, during the period of severe ice obstruction. It shows the fall in May 1901 from Lake Huron to Lake Erie, was 1.6 ft. greater than in May 1900, **nevertheless at the end of December 1901, the fall from Huron to Erie had gone back to the average of the preceding 42 years,** as shown in the original diagram by Mr. Sabin.

Although Huron drains down slowly, Erie, with its smaller area, fills up rapidly. **Each long continued ice gorge makes, for half a year, an important increase in the fall between Huron and Erie and a succession of severe winters raises the average elevation to an important amount.**

A lessened frequency of ice gorges lowers the average fall between Lake Huron and Lake Erie.

Accurate measurements of the effect of an ice gorge in lessening discharge were not made until the winter of 1900-01. It was then found that during the extremely severe and persistent ice gorge which occurred in March and April, 1901, about **two-thirds of the entire flow of the St. Clair River was held back during several weeks, and more than one-half of its flow held back for a period of from seven to eight days.**

The natural result of such an obstruction is to quickly raise the level of the Lakes Huron and Michigan by a few tenths of a foot, and to simultaneously lower the elevation of Lake Erie; but since Lake Erie has only 22% of the area of Michigan and Huron, it would drop nearly five times as fast as Huron would rise, except for the fact that the response to a diversion of water by drawing down is extremely slow in either lake, as has been explained on page 218.

GAGINGS OF ST. CLAIR RIVER 30 YEARS BEFORE

There had been gagings of discharge of the St. Clair River back in 1867, 1868 and 1869, which are mentioned briefly in the report of Chief of Engineers for 1870, page 554 to 569. Those of 1867 were made by the old Mississippi River method of double floats, and those of 1868 and 1869 were by the new method of a revolving-wheel current-meter. In fact it was here, that the superiority of the current-meter method to that by floats was demonstrated by D. Farrand Henry, U. S. Assistant Engineer. Mr. Henry described some features of this work in the Journal of the Franklin Institute, 1871.

The accurate gaging of the St. Clair, or the Detroit River, is an extremely difficult matter, requiring extensive preparation, an expensive outfit, a large survey party, many repetitions and great patience; because of the swift current, the great depth and width of these rivers, and the frequent rapid changes in stage with corresponding disturbance of velocity. It was not carried out in a conclusive way until 1889, when gagings were continued in progress for three years, 1889-1900, 1901, and all of the skill and experience developed in the elaborate Niagara gagings brought to bear on this location.

The obtaining of accuracy in the gagings themselves is only half of the problem, because there remains the tying up of the gaging to the records of lake elevation in a satisfactory way, so that given the heights in the lakes, one can be sure of the corresponding discharge, and this is perhaps the more difficult half of the problem.

Mr. Sabin sought evidence of change in regimen by comparing these gagings of 30 years before with the computed discharge at the same elevation in Lake Huron derived from the recent gagings. He reports as follows regarding this comparison: (See Chief of Engineers Report 1900, page 5,385).

> "In 1867 the measurement of discharge . . . was inaugurated . . . and observations were made upon the St. Clair River at St. Clair (about 13 miles down stream from Lake Huron) for parts of three seasons. . . . The methods employed (in 1867) were not such as to give the most accurate results, principally for the reason that . . . only a few sections were occupied in a day. The mean result of the season's work, however, must eliminate many of the errors . . . shown by a comparison of the daily discharges."

The measurements by double float, in 1867, have been corrected by standard tables published in the report of 1870 for reducing measurements by double float to those by meters for each section of the river.

The mean results of each season are as follows:

Comparison of Discharge Measurements of St. Clair River 1867–9 with 1889–01

	Mean elevation of Huron	Measured Discharge c. f. s.	Discharge by equation of 1899	Excess of later measurements c.f.s.
June–July 1867 (Floats)	581.66	221,027	226,540	+5,513
Aug.–Sept. 1868 (Meter)	580.85	216,192	211,130	—5,062
July–Aug. 1869 (Meter)	581.45	217,658	222,540	+4,822
Average for three seasons		218,292	220,070	+1,758

This agreement, within about 1 per cent, of these many separate gagings made 30 years apart, is remarkable, particularly so, because elevations taken in Lake St. Clair simultaneously with those in Huron apparently were lacking in 1867, 1868 and 1869; thus preventing the use of the latest and more accurate formulas which require elevations in both lakes as data.

The average result in the above table corresponds to a lowering of Lake Huron amounting to only 0.08 ft. in these 30 years.

This close agreement of itself is strong evidence that there had been no noteworthy change in the regimen of the St. Clair River within these 30 years; but there is doubt if these early discharge measurements were sufficiently accurate to be wholly conclusive.

Now, bringing earth-tilt into this discussion, we find that, during these 31 years between the current meter gagings, the gage at Harbor Beach from which the height of Lake Huron, chiefly controlling the discharge, was measured was about 60 miles northeasterly, measured at right angles to the probable position of the "outlet axis" of Huron, drawn through the approximate center of the discharge control section. Reckoning the rate of earth-tilt at the mean figure of 0.63 feet per 100 miles per century (see diagrams on pages 152 and 153) and giving Milwaukee and Calumet gages equal weight, this motion in 31 years would lessen the reading on the Harbor Beach gage by 0.12 ft. Therefore, all other conditions being equal, we should expect the later measurement, with water in the "bottle neck," actually 0.12 ft. deeper for same gage reading, would give a larger discharge by about 2,280 cubic feet per second, which agrees very well with the average excess of the later measurements, given in the table above, of 1,758 c.f.s.

Engineer Russell's Review

In 1904, Assistant Engineer Thomas Russell reported a new and elaborate mathematical study of discharge formulas and of ice effects upon the St. Clair River, (Chief of Engineers Report for 1904, page 4,069), in course of which he derived a new formula for the discharge, in terms of elevations of both Lake Huron and Lake St. Clair; also a new formula for the discharge of the Detroit River in terms of elevation of Lake St. Clair and of Lake Erie at the Amherstburg gage.

Mr. Russell makes plain the uncertainties of all these early discharge estimates on the St. Clair and Detroit Rivers, by a comparison, month by month for many years, of discharges computed for these two rivers (page 4,118 Chief of Engineers Report for 1904), and by showing the disagreements of the computed discharges of the St. Clair and Detroit Rivers in the same month, one computed from the St. Clair river formula, the other from the Detroit River formula.

He presented a very interesting table of elevations, going back a hundred years, also the computed discharges for the St. Clair River and the Detroit River, based on the formulas derived from the series of gagings made within the preceding three years, He noted that many of the height records before 1860 were single observations, instead of a continuous series as since 1860. Also, he made definite estimates of the retarding effect of ice, (page 4,106) and corrections to be applied to discharges computed by formulas derived in the ice-free season, which are substantially the same as the constant values of the ice correction since adopted for application in all years.

To save space these tables are not reprinted here.

It has been necessary (as explained on pages 36, 37 and 352) to adopt constant, and arbitrary, and manifestly incorrect corrections for ice, by using the same figure in all years, for a retardation, known to vary very widely from year to year, by which to lessen the discharges computed month by month from formulas established under ice-free conditions, **because of lack of information about the severity of ice obstruction year by year.**

A table was prepared (not printed) by placing these estimates of discharge of the St. Clair River made for each month by Mr. Russell, in parallel column beside the estimates of discharge for the same month made for the Detroit River, published in the 1910 Report on the Regulation of Lake Erie by the International Waterways Commission.

The average excess of discharge from Lakes Huron and St. Clair combined, as computed by the Detroit River Formula, over the discharge from Lake Huron as computed by the St. Clair River Formula, month by month, given by these tables is plotted at the foot of the diagram on page 491.

This is chiefly of value for showing the disturbing effect of the presence of ice upon the accuracy of these formulas.

Mr. Russell continued the studies of the change in regimen of the St. Clair and Detroit Rivers, and (on page 4,115) described the conditions of channel bed in much detail.

Regarding the conditions in the river bed affecting change he says (p. 4115):

> "With the greater velocities accompanying high stages, the cutting presumably is more rapid at high stages. . . . The swift current in the narrow rapids from Fort Gratiot Light House to the Grand Trunk Railway gage is an especially favorable place for this kind of action. The bottom of the St. Clair River is subject to very great changes during ice blockades, the grounded ice plowing up the bottom and the concentrated currents at constricted places cutting away soft material very rapidly."

After the great ice blockade of 1901, he says that the current through the St. Clair Flats Canal caused a deepening of several feet at places in the lower end of the canals, and says further:

> "The delta of the St. Clair River, the St. Clair Flats, is no doubt composed in part of material carried away from the banks and bottom of St. Clair River and deposited in that region. While some of the delta consists of this material, the greater part, however, is material from Lake Huron, which, shifting along the shore under currents due to waves and storms in passing across the entrance to the St. Clair River, is carried down by the current." . . .

> "In the shallow stretches of the river the propeller wheels of steamers stir up the material from the bottom, which tends to deepen the channel and increase the discharge. From the head of Russell Island to St. Clair Flats Canal—a distance of 10½ miles—the depth of the channel only exceeds by a few feet the draft of the largest steamers passing. In the last 10 years the draft of vessels passing has increased a good deal. . . . The number of steamers . . . is greater than formerly. In the season of navigation there are 33,000 vessels

passing through the Detroit and St. Clair Rivers. . . . Changes in the Detroit River are very likely to be in the same direction as in the St. Clair, but much less in amount. . . . At the lower end near Limekiln Crossing, where slope is steep and velocity of water great, at times of low water in Lake Erie, the bottom is not subject to much erosion . . . being over limestone ledge. There has been, in recent years, considerable excavation of the bottom rock in this region in widening the channel and deepening it to 21 feet. . . . The river at Limekiln Crossing is a mile and a half wide and deepening of a part 600 feet wide by a few feet would have only a relatively small effect on the cross-section."

On page 4,130 of the Appendix to the Report of the U. S. Chief of Engineers for 1904, after recounting the uncertainties that surround this matter, Mr. Russell finally says:

> **"The computed discharges of the St. Clair River being larger than those for the Detroit River can be explained by supposing the bottom of the river lower since 1893 than it was previous to that time. The differences of computed discharges for 1873 to 1892, as compared with 1893 to 1903, indicate a lowering of 0.8 feet."**

New Surveys at Outlet of Lake Huron in 1908

In 1908, the controlling cross-sections at the head of the St. Clair River were again sounded under the supervision of Mr. Sherman Moore, and a resume of the results, compared with soundings of 1899, 1901 and 1904, is given in Chief of Engineers Report for 1909, page 2,493. A comparison of these two sets of soundings showed that **in the controlling gorge at the head of the St. Clair River virtually no change in area of cross-section had occurred within these 9 years**; or to use his words:

> "For the period covered by these observations, its regimen appears to be stable."

The maximum depth of the St. Clair River in the gorge at the section 3,200 feet downstream from Fort Gratiot Light, in 1908, was found 60.6 ft. instead of 65.0 ft. found in 1899, and the 63.2 ft., in 1901, the slight filling being possibly due to a wreck lying just above.

Discharge measurements made in 1908 at the Gorge Section were found to agree with the formula established by the elaborate series of 1898–1901, for the same elevation of lake; **indicating that no change in regimen between Lake Huron and Lake St. Clair had occurred in the 8 years since 1898–01.**

OPINIONS OF OTHER ENGINEERS

In the Transcript of Testimony, printed for the U. S. Supreme Court in 1923, in the case of the U.S. Government against the City of Chicago, several experts present data and opinions and give a review of the hydraulics of all of the Great Lakes.

Mr. Gardiner S. Williams (Transcript, page 755) testifying on July 18, 1913, concluded that the deepening of these channels between Lake Huron and Lake Erie **might have lowered Lakes Huron and Michigan anywhere from 0.6 ft. to 1.2 ft., probably not over 1.0 foot;** and found the most marked change occurred about 1889 to 1891, **at a time toward completion of the channel improvements; when the controlling sections or crests of the "submerged weirs" were cut away.**

Mr. Williams (page 704 of Transcript) noted that engineers in charge had reported a total of 15 million cubic yards of material removed from St. Clair and Detroit Rivers **since completion of discharge measurements in 1902,** all within a length of 20 miles and equivalent to a channel 600 feet wide deepened 6½ feet. This statement by itself would indicate that the discharge formulas for the Detroit River established prior to 1902 are not strictly applicable since 1913, but on the other hand an inspection of the navigation charts shows that **much of this material was put back within the river outside of the navigable channel.**

Mr. Williams also noted **that the channel within the bar across the entrance of the St. Clair River in Lake Huron, had been deepened 10 ft.**

Also, he refers to the Report of Chief of Engineers for 1911, page 3,013 and says, "**The effect of this work has been to increase the discharge of the St. Clair River for the same stage about 3 per cent . . . which is about 5,700 c.f.s.**"

This quantity of water corresponds to an increased depth of 0.30 ft.

Mr. Williams (page 706) concluded that the great and sudden drop in relative level of Lake St. Clair, amounting to 1.82 ft. between two 6 years periods, 1884–9 to 1890–5, was **probably largely due to dredging at the Limekiln Crossing,** and that this had increased the discharge of the St. Clair River for the same elevation of Huron, and therefore that this dredging had contributed materially to the lowering of Lake Huron.

Mr. F. P. Stearns (see page 1,014 of the Transcript) said:

> "There have been deepenings and improvements in St. Clair and Detroit Rivers, and improvements of channels, which **makes any equation deduced from measurements in the years 1899 on, not inapplicable to the earlier years.**"

On page 1,036 of the Transcript, Mr. Stearns testifies that he found a **probable lowering of 11 inches in Lake Huron,** and concluded that the estimates of discharge of Huron in the early years based on elevation and recent gagings, were too large, and, on page 1015, says,

> "That the channels of the St. Clair and Detroit Rivers were smaller in those early years (1883 to 1888)."

Mr. Stearns' Exhibit, "Table G," indicates a change of about 17,800 c.f.s. in the channel discharge capacity of St. Clair and Detroit Rivers between 1883–1888 and 1892–1893.

For completeness it should be added that Mr. Stearns, in 1913, in trying to explain the apparent small water yield of the local Lake Erie drainage, which was often given as negative by the Lake Survey estimates, concluded (page 1,015) that **either the St. Clair-Detroit gagings must be too large or the Niagara gagings too small,** and because of disturbances at the Niagara gaging stations, the Niagara gagings were the ones which he then thought probably in error; concluding that the Niagara yield as measured, was shown to be about 18,000 c.f.s. too small, by deductions which he made from the St. Lawrence River gagings, and his estimate of probable contribution from the local Ontario drainage area, after allowance for probable evaporation.

The present writer, also, was one of the experts called in this litigation, in 1913, and at that time doubted the precision of the Niagara gagings because of eddies and disturbed currents. His recent painstaking review of all of these hydraulic studies of the channels connecting the Great Lakes has materially changed his views. He now regards the formulas or discharge curves deduced from current-meter measurements on the St. Clair and Detroit Rivers, as presenting a much larger margin of uncertainty than those on the Niagara River, and that the anomalous deficiency of net yield of Lake Erie and its local water shed, are to be explained mostly by an over-estimate of perhaps 20,000 c.f.s. much of the time, even in the open season, in published estimates of the discharge from Lake Huron, particularly in the early years.

He now believes **the Niagara gaugings are correct within a margin of not exceeding 2 per cent;** by which amount they possibly may be too small, because of the under-registering of the water meters in the probably disturbed currents near the bottom of the river, and regards these three concurrent sets of Niagara gagings as at the Bridge Section, Open Section, and Split Section, **the most successful example of gaging the flow of a great river with extreme precision that has ever been made.**

Review in the Warren Report

Mr. W. S. Richmond, pages 356–357–358 of the Warren Report, discusses this matter of lowering of Lakes Huron and Michigan and of change in the river beds. He says:

> "It appears probable that there have been some changes in the regimen of the St. Clair and the Detroit Rivers since the first gage records on these rivers were obtained. In the case of the St. Clair River these have probably not been large, and **there have been no changes of moment due to improvements for navigation purposes since the construction of the canal at St. Clair Flats.**

He says further:

> "Small changes in the regimen apparently occur from year to year due largely to movement of the material which overlies the true bottom. During storms some material, principally sand and gravel, is brought into the river from the shores of Lake Huron, and is carried from point to point down the river by varying velocity and direction of the current. Bars are built up along the shores in the rapids at the head of the river in the fall, but are of short duration.
>
> "Dredging on Black River shoal and in the river above it, appears to have but little effect on the depth. . . .
>
> "The measurements of flow made in 1902 compared with those made in 1901 show a change in discharge capacity of about 3%, while the measurements of 1909 and 1910 are about midway between those of 1901 and 1902. (This indicates that in these 8 years there was no noteworthy change of regimen.)

"In 1898-1899 four sections were established near the head of the river, and were very carefully sounded. Soundings made since on these sections indicate that there has been no measurable change in the cross-section of the river.

"In the Detroit River there has probably been less change in discharging capacity due to natural causes than in the St. Clair River, but the changes due to improvements for navigation and other purposes have undoubtedly been larger. The construction in 1872 of the bridge at Trenton west of Grosse Isle and the pier extending some 1,300 feet into the main channel from Stoney Island materially decreased the cross-section of the river, and the encroaching dock line along the Detroit River front and some large fills on the Canadian side have further lessened the discharging capacity.

"The construction of the Belle Isle Bridge in 1889 obstructed an appreciable part of the cross-section of the channel west of Belle Isle, and must have had some effect on the discharging capacity of the river."

Mr. Richmond concludes:

"Whether or not there has been any marked change in the level of Lake Huron due to change in regimen of its outflow channel is still a mooted question, and probably will remain so unless the stages of the Lakes should return to the high levels of the 80's. **It is reasonably certain, however, that there has been no great amount of change in the discharging capacity of the St. Clair and Detroit Rivers.**

"On the other hand, dredging at Limekiln Crossing and at other points has tended to increase the capacity of the river.

"Thus the Detroit River has undergone a number of minor changes in regimen, the effect of which has been compensating to a considerable extent.

"The greatest change in regimen, and the only one of which the effects were directly observed, was that occurring in the years 1908-1911, when the cofferdam around the upper section of the Livingstone Channel was in place. . . . The rise at St. Clair Flats was observed to be 0.28 foot. When this cofferdam was cut, in 1912, Lake St. Clair dropped back to its natural level, thus showing that the remaining portions of the cofferdam, together with the judicious placing of spoil, had exactly balanced the effect of the new channel. . . .

"That there has been any large change in the discharging capacity of the St. Clair-Detroit River appears improbable."

Mr. Richmond discusses the effect of ice in raising the level of Lake Huron, on pages 360-363 of the Warren Report. Having first shown that the obstructions of ice-cover and ice-gorges which vary greatly from year to year and sometimes change rapidly from day to day, probably lessen the discharge by 10,000 cu. ft. per second as an average spread over the whole year, he shows that a change in climatic effect such that if instead of the average estimated amount of retardation of the outflow by ice, amounting to 10,000 cu. ft. sec., in the average year, all of this ice obstruction should suddenly cease, then a new state of equilibrium would slowly develop under which the mean elevation of Lake Huron would be 0.48 foot lower than before.

Since in some winters of extreme severity the lessening of discharge is double that in other winters, and since **the readjustment of level downward is much slower than the rise caused by an obstruction,** he makes it plain that a succession of severe winters each with a long period of ice obstruction would cause a noteworthy rise.

Mr. Richmond concludes, after plotting the comparative heights of Lake Erie and Huron grouped into four main periods, **that a lowering of Lake Huron of about three-tenths of a foot relative to the elevation of Lake Erie is apparent, but not well established.**

DIAGRAMS COMPARING HEIGHTS AND FALLS BETWEEN LAKES HURON AND ST. CLAIR AND ERIE

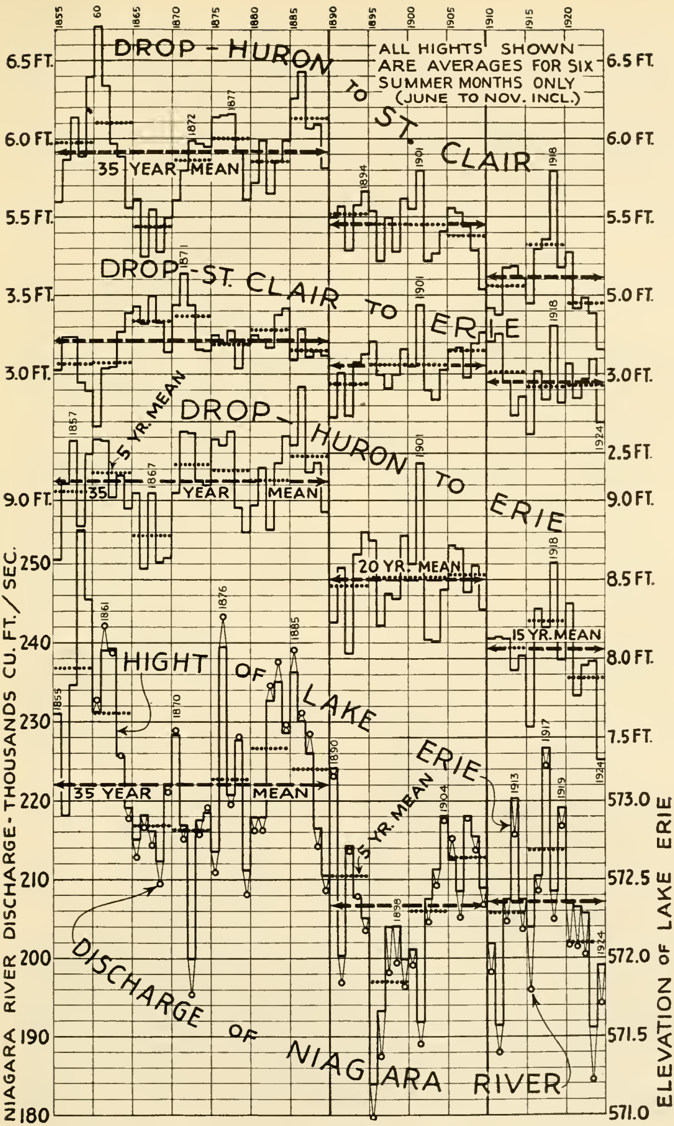
Prior to his studies of earth-tilt, the present writer had replotted all of these heights and falls between Lakes Huron, St. Clair, and Erie by the individual summers, with several different arrangements in order to more clearly bring out, if possible, the time when the change occurred, and thereby connect it with the dates at which dredging was carried on, or in which exceptional ice gorges led to unusual scour of the river bed.

Apparent Slowly Lessening Water Yield

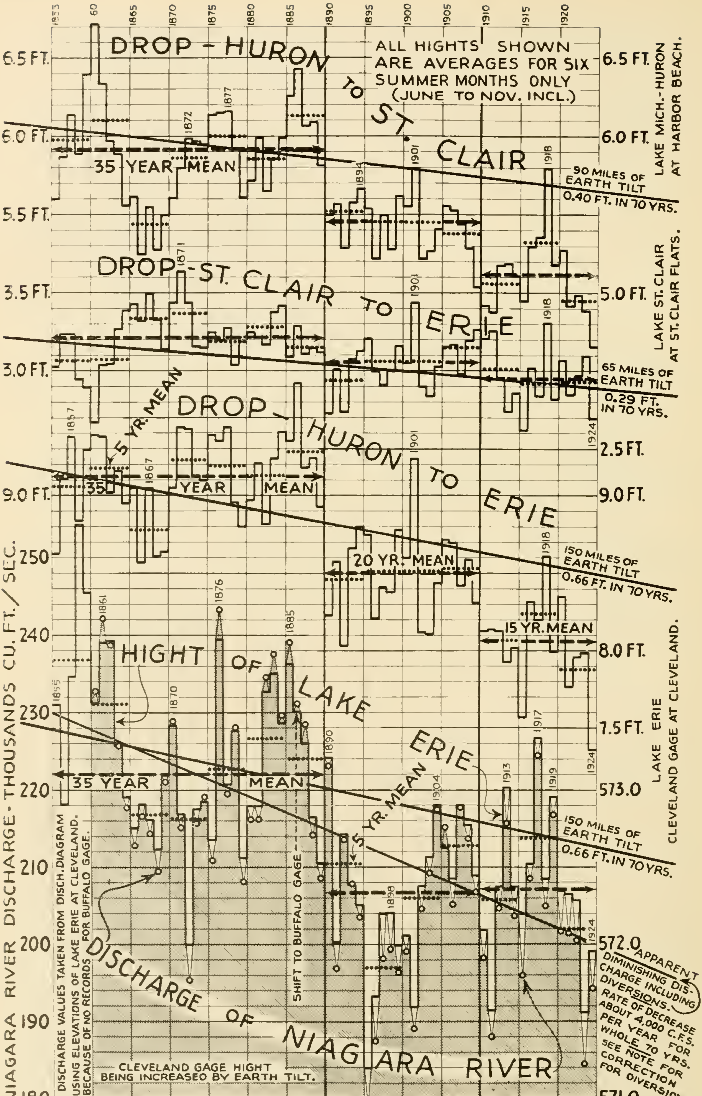
The first of these two similar diagrams was prepared without reference to earth-tilt, while in the second diagram lines have been drawn and shading added to clearly show the effect of earth-tilt and of the gradual diminution of the quantity of water discharge by the Niagara River. At first view, this seems to have proceeded irregularly resulting in a total diminution in 70 years of 28,000 cubic feet per second, according to this diagram, but of this total, one-half is accounted for by the diversions by the Chicago and Welland Canals. The increased draft for power at Niagara has of itself lowered Lake Erie by about 0.10 ft., by giving steeper slope to the river through this gorge at the outlet of Lake Erie, and causing the diagram made from measurements of about 20 years ago to show too small a discharge when applied to recent years.

This corrected rate of diminution of 200 cu. ft. per second per year, or 14,000 second feet in all, can not be accepted as fully proved, because the early gage heights are less reliable, and there may be some error in extending the appreciation of the recent discharge formulas back so far, moreover, this diminution in water yield does not fully concur with the comparisons on pages 491 and 492 which seemed to prove that no important permanent change in lake heights (and therefore in yields) had taken place in a hundred years. This apparent diminution, although small, at least, is suggestive, and perhaps can be explained in part by the increased cultivation of the land.

And, shifting the location of the gage used for estimating the discharge from Cleveland to Buffalo in 1886, has caused another disturbance of rate. These early gage readings should be corrected for earth-tilt prior to use with the discharge diagrams referred to the Buffalo gage.



RELATION OF DROP BETWEEN LAKES TO TIME AND TO QUANTITY DISCHARGED



RELATION OF DROP BETWEEN LAKES TO TIME
AND TO QUANTITY DISCHARGED

Changes Shown by Preceding Diagrams

The two diagrams on the preceding pages are believed best for making the main facts apparent.

They seem to show that a remarkable change occurred, about 1890, in fall between the lakes and in average water yield of the Great Lakes.

This time and height diagram shows an important change all along the line about 1890 and another about 1910. Their horizontal average lines for the three periods show the following changes.

For Six Summer Months, June to November, inclusive	Period 35 Years 1855 to1889 Inclusive	Period 20 years 1890 to 1909 Inclusive	Period 15 Years 1910 to 1924 Inclusive
	Feet	Feet	Feet
Average drop, Huron to St. Clair	5.91	5.45	5.11
Average drop, St. Clair to Erie	3.21	3.06	2.95
Average Drop, Huron to Erie	9.12	8.51	8.06
Change in drop, Huron to St. Clair, 1890	0.46	....	....
Change in drop, Huron to St. Clair, 1910	....	....	0.34
Change in drop, St. Clair to Erie, 1890	0.15	....	....
Change in drop, St. Clair to Erie, 1910	....	....	0.11
Change in drop, Huron to Erie, 1890	0.61	....	....
Change in drop, Huron to Erie, 1910	....	....	0.45
Average Height of Lake Erie	573.10	572.34	572.37
Average Discharge of Lake Erie	222,000	206,800	207,000
Change in Elevation of Lake Erie, 1890	—0.76	....	....
Change in Elevation of Lake Erie, 1910	....	....	+0.03
Change in Discharge of Lake Erie, 1890	—15,200	....	....
Change in Discharge of Lake Erie, 1910	....	....	+200.

If other conditions, such as ice effect, were constant, these changes in Erie should not affect the drop between lakes. The diagrams on pages 491 and 492 bring out the fact that they are greatly disturbed from causes not fully known, but probably they are chiefly caused by ice gorges or more or less complete ice cover during the preceding winter.

This method of plotting each year separately gives a confused diagram, but by showing up the departures, year by year, from the long-term average, this method of analysis reveals the irregularities and uncertainties which become concealed in long-term averaging.

The average of the 6 ice-free months, June to November inclusive, was used instead of that of the full year, for the purpose of avoiding the abnormal conditions of excessive fall known to occur during an ice jam, **but the increased fall continues long after the ice that caused it has disappeared.** The diagram, on page 500, shows that the result would not have been changed materially had all the months been included, and an arithmetic average of all the values in the tables shows surprisingly little difference between the average fall in the two six-months periods comprising December to May, and that from June to November inclusive.

By each of the three diagrams of comparison of elevation and fall which follow on pages 520 and 522, it is seen that the amount of fall between Lake Huron and Lake Erie is greater when the lakes are high than when the lakes are low, and that **a cycle of low lake levels was beginning at about the time of greatest decrease in fall between Huron and Erie.** Also that it happened that nearly all of the observations prior to 1890 were comprised within a period of high lake levels, while those subsequent to 1890 fall mostly within a period of low lake levels. This is unfortunate for purposes of comparison.

Whatever the amount of lowering of Lakes Michigan and Huron that has been caused by dredging and natural scour in the beds of the St. Clair and Detroit Rivers, **this has been obscured and made difficult of precise measurements because of the general lowering of all lakes except Superior that has been caused meanwhile by climatic changes.**

Reasons for Expecting No Change in Fall

If there had been no important deepening of the outlet of Lake Huron there would be good reasons for expecting no change in the fall from Lake Huron to Lake Erie, notwithstanding the annual water yield of both lakes should change in some proportion, because of change in climatic conditions; but this does not appear borne out by observation.

The diagram of current-meter gagings in the head of the Niagara River, on page 30, show with excellent precision that over a range of about four feet in the height of Lake Erie, or from elevation 570 to 574, the discharge increases in nearly a straight line from 155,000 c.f.s. to 241,000 c.f.s. This increase of 86,000 c.f.s. in discharge for four feet rise, gives an average increment of discharge, for each foot of increased elevation of lake, of .... 21,500 c.f.s.

Similarly the original discharge diagram for Lake Huron outlet in the Chief of Engineers Report for 1900 following page 5,400 shows:

For elevation, 581.7, a discharge of .... 219,000 c.f.s.

For elevation 579.5, a discharge of .... 177,000 c.f.s.

Or for range of 2.2 ft. an increase of .... 42,000 c.f.s.

Which gives for each foot of increase in height an average increment in discharge of .... 19,000 c.f.s.

Since the drainage area discharging at Huron is smaller than at Niagara a compensation should be made in the average ratio of the Huron discharge to the Niagara discharge, which for 60 years, is as 181,400 c.f.s. to 207,900 c.f.s, or 87.3 per cent.

Therefore when Lake Erie's discharge is increased from natural causes by .... 21,500 c.f.s.

The Huron discharge should proportionally increase by 87.3 per cent x 21,500 equals .... 18,780 c.f.s.
which is almost precisely the same as the average increment for the outlet of Huron found above.

Repeating this estimate for 25 years, instead of for 60 years, as above (because the corrections for ice and the estimates of discharge are probably more accurate for the past 25 years than for the 60-year period) gives a ratio of 179,800 c.f.s. to 205,600 c.f.s., or 87.4 per cent., instead of the above 87.3 per cent., which applied to the Niagara increment of 21,500 gives 18,800 for Huron.

Either this 18,800 or the above 18,780 is remarkably close to the 19,000 increment deduced for Huron above.

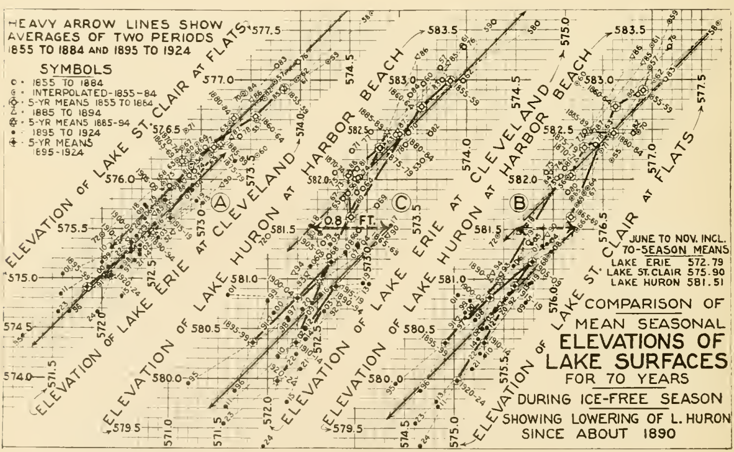
The same concurrent relation is shown by the lines for Erie and Huron in the diagram on page 212.

Therefore, as stated above, **there was good reason to expect a constant fall from Huron to Erie, regardless of the average annual water yield.** Also, in drawing a line on the diagrams on page 518 for the purpose of averaging of the two sets of observations before and after 1900 the line should be drawn on a one-to-one slope.

RELATION OF AVERAGE LAKE HEIGHTS

The diagram below contains three separate diagrams in parallel, each showing the relation of one lake to another in heights, made up by plotting and averaging the average monthly heights during the ice-free season observed in each separate year. **The central diagram shows the changing relation of Huron to Erie, which resulted in the discussion by various authorities** which has been reported in the preceding pages. The diagram at the right shows the relative heights of Lakes Huron and St. Clair year by year; and at the left is a diagram showing the relative heights of Lakes St. Clair and Erie. Each of these diagrams is of a similar make-up to that presented by Mr. Richmond, plate No. 53, accompanying the Warren Report, from which he deduced a lowering of 0.3 ft.

In the present diagrams the observations for each year are plotted individually instead of as averages, in order to bring out their lack of agreement.



Two sets of plottings are superimposed. The first shows mean heights for the two lakes in each individual year, and the second shows the same for five-year means. Through the entire series prior to 1890 a line is drawn upon a one-to-one slope, as described in a preceding paragraph and averaging all of the observations.

It is believed wise to thus show how widely the comparisons scatter, lest one be misled about the precision that can be obtained, as may happen when one plots only the 5-year or 10-year means.

The observations subsequent to 1890 are similarly averaged by a line on a one-to-one slope, but in each case the points for the years of transition from 1885 to 1895 are not given weight in the average.

The average lines for the respective groups, shown by the arrows, before and after 1890 do not coincide, and the distance between them measured horizontally shows the amount by which the relation changed at about this time. The central diagram shows that **for the later period Huron was eight-tenths of a foot lower relatively to** a foot higher relative to Lake Erie, than in the second period.

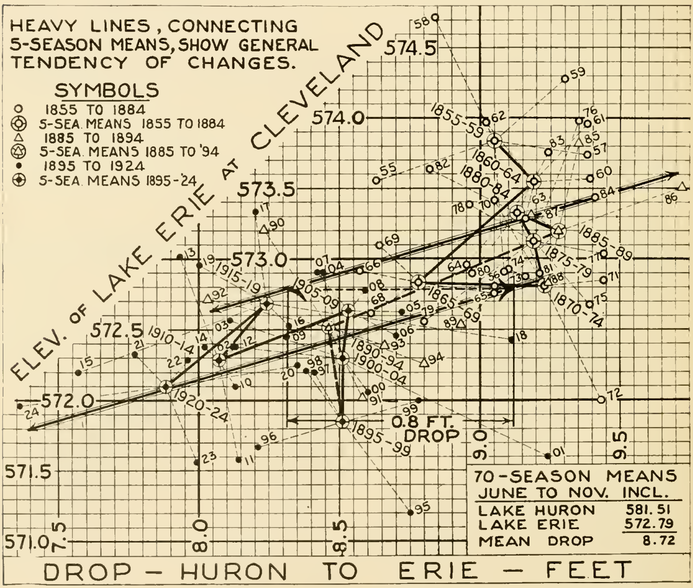
Remembering that Erie is our datum for comparisons, the diagram at the left shows that in the first period St. Clair stood two-tenths of a foot higher relative to Lake Erie, than in the second period.

The diagram at the right shows that Huron stood six-tenths of a foot higher relative to St. Clair in the first period than in the second. In other words, these three diagrams indicate that the amount of eight-tenths foot by which Huron became lower in the second period was not equally divided between the St. Clair River and the Detroit River, and that the change was three times as great above the St. Clair Flats gage as below it.

An arithmetical average of the tabulated heights of the lakes for the two periods also shows a change of 0.8 foot.

RELATION OF DROP TO TIME

In the following diagram, because of regarding Erie as the most reliable datum for comparison, the fall from Huron to Erie is plotted year by year for 70 years, in terms of the height of Lake Erie, in an effort to trace out more definitely the change from year to year. Also the means for each five-year period are shown with lines radiating out to points for each of the years averaged, which serve to show the wide variation in fall from one year to another, caused by ice, wind, etc.



MEAN SEASONAL CHANGES IN FALL FROM HURON TO ERIE FOR 70 YEARS, 1855 TO 1924, DURING ICE-FREE SEASON SHOWING LOWERING OF ERIE SINCE ABOUT 1890

A heavy line connects these five years means in orders of date. It will be noted that this returns on itself in an irregular way, and that there was no change in fall between Huron and Erie, in the 20 years from 1860–64 to 1880–84, also that in the 30 years from 1855–59 to 1885–89 the change in drop from Huron to Erie increased from 9.05 to 9.28 ft, or 0.23 feet, although Erie stood more than a foot lower in the second period. No explanation is found for the fact that the 5-year group, 1865–1869, shows consistently nearly half a foot less average fall than in the other 25 years.

The observations of the 45 years, 1855 to 1889, form a group distinct from the later observations, and throughout this period with the one exception noted (1865–9) the drop between lakes remains nearly constant at about 9.25 feet regardless of the general rise or fall, and regardless of the discharge in the Niagara River.

The later observations divide themselves into two distinct groups. It seems highly probable that some change in the river bed must have occurred within the time between these groups, which separated the observations into these three groups.

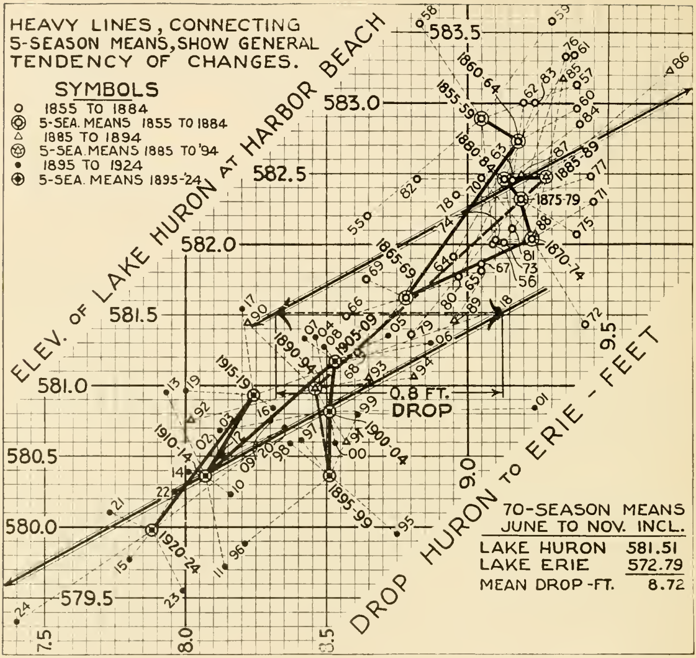
The group comprising 20 years from 1890 to 1909 inclusive shows a nearly constant drop of 8.5 feet, with but little relation to changes in height of lake Erie.

The third group comprises the 15 year period, 1910–1924, with an average of about four-tenths of a foot less drop for the same level of Lake Erie.

The discordance of the mean 1915–19 appears due to some abnormal happening in the year 1918. The opposing peaks O and DD in the diagram on page 492 **indicates that the cause was a severe ice jam in the St. Clair River,** which held back water and raised Huron and Michigan to the greatest height within about 30 years, while lowering Erie by depriving it of normal inflow, and from which disturbance it took a year or more to recover.

From the care taken to obstruct the Detroit River outside the new Livingstone Channel, with material excavated from the Livingstone Channel, it may be accepted as a fact that the opening of this channel did not cause any important part of this apparent lowering of Lake Huron, relative to the Cleveland gage. The earlier deepening in the St. Clair River delta and perhaps that at the Limekiln Crossing may have been contributing causes.

The following diagram, giving the fall from Huron to Erie plotted in terms of Lake Huron, is included to show that the same results would be obtained regardless of which lake was chosen as the datum for comparison.



MEAN SEASONAL CHANGES IN FALL FROM HURON TO ERIE FOR 70 YEARS, 1855 TO 1924, DURING ICE-FREE SEASON SHOWING LOWERING OF HURON SINCE ABOUT 1890

EFFECT OF EARTH-TILT ON APPARENT DROP

The amount of earth-tilt measured by the concurrent testimony of 20 pairs of gage comparisons, some of which gages have been observed continuously each day for 50 years, and with very particular care as to precise accuracy and reference to permanent bench marks during the past 25 years, **prove conclusively that earth-tilt has been going on throughout all of this Great Lakes region.**

The fall between these lakes has been measured by differences between the Harbor Beach and the Cleveland gages.

The Harbor Beach gage has been continuously raised so as to read less, by this tilting and the Cleveland gage has been made to read more by this tilting, so that if the observations be grouped into two main divisions, those prior to 1890 and since 1860, into one group of 30 years; and those since 1890 to 1924, into another group of 34 years; the averages of the two groups will be 31 years apart and at the probable mean rate of about 0.63 ft. per 100 miles per century for the Michigan-Huron region and 0.63 ft. per 100 miles per century for the Lake Erie region, and allowing for the respective distances of these gages from the outlet axes of Lakes Huron and Erie, it appears definitely proved that within this period the Harbor Beach gage has come to read 0.12 ft. lower and the Cleveland gage 0 29 ft. higher, **earth-tilt thus accounting for 0.41 of the discrepancy** of about 0.8 ft. (or possibly 1.0 ft).

The remainder of the observed lowering after correcting for earth-tilt, 0.39 ft., may reasonably be divided between

(1) A smaller average rate of discharge

(2) Deepening of channels by dredging

(3) Natural scour following this removal of the protective coat by dredging.

(4) Greater average ice obstruction in the earlier years. (Doubtful?)

The lowering of Lakes Michigan-Huron caused by diverting the amount of 4,167 cu. ft. per sec. at Chicago is known with certainty to be 0.20 ft.

The present writer believes it is certain that causes 2 and 3 noted above, have lowered these two lakes Huron and Michigan, to an extent of at least 0.2 foot (possibly 0.4 foot) and therefore that the effect of dredging has at least lowered these two lakes as much as the diversion of the 4,167 cu. ft. per sec. authorized.

APPENDIX NO. 4

STUDY OF EFFECT OF CHANGE IN FOREST CONDITION UPON RAINFALL AND RUN-OFF

The cutting off of the great forests has often been suggested as a possible cause of the lowering of lake levels.

Any important change in forest influences, either upon the total rainfall received, or in the loss by transpiration and evaporation between rainfall and run-off, should be reflected either in a change in the total annual rainfall over a term of years, or more probably in a change in the annual net water-loss found by subtracting from the measured depth of total annual rainfall over the whole region, including land and lake, the total annual average depth of run-off computed from the outflow at the outlet of each lake, measured at the several gaging stations in the St. Mary's, St. Clair, Niagara and St. Lawrence Rivers.

If the totals of these quantities for one year periods are too irregular to show clearly the time or amount of change in water-loss between rainfall and run-off, five year totals or averages should make apparent any important change.

If the cutting off of the tall pine trees at the remarkably rapid rate known to have taken placed between 1870 and 1890 in northern Michigan, northern Wisconsin and adjacent to Lake Superior, actually lessened the loss of water by transpiration to any important degree, this should be reflected in increased run-off, unless transformation meanwhile of large areas into farm land has increased the net water-loss from ground thus exposed or covered by crops which involve large transpiration.

As a matter of fact, this transformation of pine forest into open cultivated field during this period covered a relatively small portion of these drainage areas. Moreover this transformation proceeds at a very slow rate, and in general it will be found that **for many years after being logged off a territory presents a covering of small trees, underbrush and verdure which shade the ground nearly as effectually as the tall forests.** Often these smaller growths of verdure spring up with remarkable luxuriousness and rapidity when the shade of the tall trees is removed, and often the soil moisture which the tall trees had sucked out of the ground from time immemorial becomes available for other tree growths, underbrush and weeds.

The following diagrams give the results of a computation made for each year, and for each separate lake. After trial, the separation of the water-yield of the Michigan-Huron area from the Erie drainage was given up because of lack of accurate information about the discharge of the St. Clair River from 1860 to 1900 and the extent to which deductions should be made from the nominal flow computed by formula from lake levels to compensate for the obstruction presented by ice cover and occasional ice gorges.

Since the year 1900 the Lake Survey has given much closer attention to correct estimates of lake discharge, and a separation of Erie from Huron-Michigan yield has been made for the past 25 years.

The results set forth in the following diagrams are extremely interesting and present a degree of regularity far greater than it was expected to find in the total annual water-loss in inches depth from year to year, from the earliest to the latest gagings.

As noted elsewhere (on page 43), a general decrease in the annual rainfall is found during this period. This decrease is shown in greater detail in the diagrams which follow. It is believed to be temporary, because of the gages in New England having indicated no permanent decrease for about 150 years past, but only widespread cycles, and because of the further fact that the early years of these Great Lake rainfall records appear to have fallen at a time of greater than average precipitation.

The water-losses shown, from year to year, are remarkably constant, and as a whole the results of the computations presented in these diagrams tend to give great confidence in the accuracy of the data that have been used, both of stream flow and of rainfall measurement.

The writer can find in these results no indication that the cutting off of the forest has had any noteworthy effect upon lake levels or upon the water yield of the higher Great Lakes drainage regions as a whole.

MORE DATA DESIRABLE UPON EXPOSURE OF RAIN GAGES

The well-known differences, caused by height and exposure of rain gages have led the present writer during many years of practice to cause an inspection to be made, in important cases, of each rain gage within the area under investigation, including photographs and precise data as to diameter, elevation, exposure of gage to winds, eddies, etc., wherever practicable, in order that greater or less weight could be given to individual records while drawing isohyetals or computing averages. In the present case no information has been available for showing differences in quality of data obtained at the 50 or more stations, or the extent to which allowance should be made in individual records for exposure, shelter, elevation or type of gage, and care or skill of observer, or for systematic error in measuring the equivalent depth of melted snow. The following notes will show that **conditions of this kind should be considered in all work that aims to attain high accuracy.**

EFFECT OF ELEVATION AND EXPOSURE TO WIND

The observations by Desmond Fitzgerald (See Jour. Assoc. Eng. Soc. 1884, p. 233) of Prof. Francis E. Nipher of St. Louis, (Jour. Am. Assoc. Adv. Science 1878, p. 103), and sundry other observations, particularly in England and France, have shown that an elevated gage commonly gives a smaller depth than a gage near the level of the ground, a difference of 10 per cent being not uncommon. Later observations prove this difference is mainly due to the effect of the greater velocity of the wind at the higher exposure, the deflection of air over top of gage, and the consequent deflection of the smaller rain drops from entering it.

Fitzgerald's observation on two gages at the Chestnut Hill reservoir near Boston each 14.85 inches diameter, one at 3.0 feet above the ground, and the other 20 feet 4 inches higher, gave about 10 per cent smaller rainfall by the higher gage. In general, differences were greatest with the higher winds.

A particularly noteworthy example presented by Mr. Goodnough in Jour. New England Water Works Assoc. 1926, page 181, is that of the gage at Plum Island. This gage **set on a treeless mound collected practically no rainfall in heavy storms,** whereas a gage set in a reasonably sheltered location nearby gave a result comparable with those of other gages in the region about it.

The best presentation of this matter known to the writer is by Professor Cleveland Abbe of the U. S. Weather Bureau, presented as Appendix 1 to Bulletin 7, on Forest Influences, by the U. S. Dept. of Agriculture, 1902, comprise about 200 pages regarding the various influences of forests upon temperature, rain, floods, etc. This paper of Professor Abbe's reviews many observations, chiefly in Europe, and attributes the diminution in high wind to the **increased air-velocity over the top of the gage** caused in going over the obstruction. This carries forward the smaller drops, and prevents some from falling inside, as they would do in still air.

The present writer believes this condition is increased by the upward deflection at the upstream edge, in a way that makes the effect relatively larger with gages of small diameter.

Another study of forest influences upon rainfall, run-off, etc. not yet completed, is described in Supplement 17, to the Monthly Weather Review for 1922, which presents results of 8 years observations upon two similar areas, each of about 200 acres, at Wagon Wheel Gap, Colorado, and cites many European observations.

EFFECT OF DIAMETER AND TYPE OF RAIN GAGE

At certain exposures differences in diameter of gage appear to have caused important differences in the record of gages placed side by side. Illustrations of this are presented in a paper by X. H. Goodnough, on "Rainfall in New England" in the Journal of the N. E. Water Works Association for June 1926, page 180, as follows:

At Pawtucket, R. I.—	10 years observations during the months of no snowfall gave 3.3% more rainfall by a gage of about 15 in. diameter in comparison with the standard 8-inch gage. During 1913–14 the full year's record showed 8.2% larger precipitation by the larger gage.
At Taunton, Mass., since 1920—	13.2% more rain was caught by a large gage (14.25 in. in diameter) than by a standard 8-inch gage of U. S. W. B. pattern.
At Lowell, Mass., at the Locks and Canals dam—	The gage of 14.5-in. diameter gave a larger collection of rainfall than the standard 8-inch gage.
At Ludlow reservoir of the Springfield Water Works—	In a comparison between shallow gages 8 in. in diameter and 3 in. diameter, the shallow gage gave about 10 per cent less than the standard 8-inch gage.
On the other hand, Comparisons at New Bedford, Cambridge, Groton and Leominster—	Showed practically the same results by the standard 8-inch gage and smaller gages set side by side.

Many more comparisons of this kind with fuller particulars, photographs and isometric perspective sketches are strongly needed.

The above differences emphasize the **great importance of care as to the exposure of a gage to wind currents,** and when one considers the altitude and location at which many of the gages from which these data on rainfall have been derived, it is plain that one of the first steps toward greater precision in estimating relation of rainfall and run-off on the Great Lakes should be an inspection of each rain gage whose record is used, and the setting up of a check gage for a few years of comparison, at all doubtful stations.

The accuracy of rainfall observations also depends largely on the faithfulness of the observer. A carelessly kept record may be worse than useless because it is misleading. The writer has occasionally found cases in which low annual, or monthly, totals were caused by temporary absences of the observer.

Our safety in the present estimates lie in the fact that observations for more than 50 different rain gages have been averaged, and a few apparently abnormal records rejected.

Because of the fact that many of these gages are in exposed localities, and some at a considerable elevation above the ground, the probabilities, in the writer's judgment, are that the final average record adopted is slightly less than the true average precipitation on land and water.

SEASONAL DISTRIBUTION AFFECTS RUN-OFF

If the great rainfalls occur during the months of May to September, when crops and plant life in general are growing, then the run-off will be less than if the same depth of precipitation occurs during the winter or spring, when the percentage of run-off is the highest. Snow of a stated equivalent depth will not affect the run-off in the same manner as rain, because of its being held over a long period; meanwhile perhaps largely disappearing by evaporation.

VARIATIONS IN ANNUAL RAINFALL

Records of rainfall in eastern Massachusetts and other New England States dating back about 150 years show no evidence of an increase or a decrease in the rainfall, and that there is no marked evidence of a change in seasonal distribution. The variations in the annual quantities are usually comprised in short and irregular cycles, and periods of high and low rainfall seem to occur about every 10 to 14 years.

It is observed that there was a dry period in New England about 100 years ago, from about 1816 to 1849, of fully as great intensity as that of the present time. The greatest annual rainfall during that entire period was not so great as that in 1916, 1919 or 1920 of the present dry period. Neither of these two dry periods was probably so severe as that which occurred about 1760–82 and which was at its lowest about 1762.

RELATION OF FOREST COVER TO RUN-OFF

The comprehensive studies of the water yield of the Merrimack River in New Hampshire and Massachusetts by Lieut.-Col. Edward Burr in House Doc. No. 9, 62nd Congress, 1st Session, transmitted to Sec. of War on March 6, 1911, relative to improvement of this river for navigation; present in the judgment of the present writer by far the best guide to the effects of cutting off timber and developing farm lands in the Great Lakes region that can now be found outside the records of run-off of the Great Lakes drainage given elsewhere in this report. On page 7, et seq., this report of Colonel Burr presents a study of forest influences on the yield of the river, made under his supervision by Mr. H. Edgecomb and Mr. F. O. Stevens.

Water-power development, begun more than 100 years ago on this river, has resulted in 100 years of rainfall records and 75 years of careful gagings of river flow.

Although the rainfall records were few until within about 40 or 50 years, Colonel Burr says:

"The circumstances of this case are such as to furnish an opportunity better than exists elsewhere in the United States for the study of the relation of forests to stream flow on a stream of such size as to warrant it being classed as a navigable river.

"Deforestation progressed continuously from time of early settlement and reached its maximum between 1860 and 1880—with decline of agriculture extensive tracts have reverted to forest and sprout land since about 1870, so that in 1910 forest areas were believed 25 per cent greater than 40 years before."

The drainage covers above 5000 square miles.

Colonel Burr concludes, page 19:

"Nothing in the facts found as a whole gives any support to the general popular belief that deforestation has exerted a harmful, and reforestation a beneficial effect upon stream flow insofar as concerns the Merrimack basin."

The present writer, 50 years ago, had an important part in making up the stream flow records of the Merrimac River and has a broad familiarity with the topography of its water shed, and has often considered the condition and effect of its forest and "sprout-land" cover, as affecting the rainfall and run-off upon this Merrimack drainage area and others in New England. He has travelled much in the areas around the Great Lakes and considers conditions upon the Merrimac drainage more fairly comparable than any other available data. Although the extreme head waters of the Merrimac are in the White Mountains, the mountainous area in the Merrimac drainage is a small part of the whole.

The forest cover of the entire Merrimac area was estimated as 62 per cent of the whole (p. 16 Burr Report).

The relation of run-off to rainfall was found not to have changed materially with the 25 per cent increase in forest cover during a period of 40 years (p. 30).

The average of run-off from the land, including lake areas aggregating about 8 per cent of the whole, was found to have been about 55 per cent, or 23.3 inches run-off from an average precipitation of about 42.4 inches.

LONG TERM TENDENCY TO CHANGE IN RAINFALL AND WATER-LOSS

The first of the following diagrams shows the long term changes in total annual water-yield of the Great Lakes, in average cubic feet per second, as computed by the best data available. The average annual quantities discharged have been previously presented in the diagram on page 235, but without adjustment for diversions or changes in elevations of lake surfaces. The adjusted yield of the Lake system above Niagara, in connection with the mass curve diagrams, is given for the past 65 years on pages 354 to 365.

It was thought that a separate analysis of the yield from the drainage area of each lake and its tendency to increase or decrease would be of interest, and show any special discordance between the estimates from year to year.

Obviously, the estimation of these quantities of water discharged involves applying formulas, derived from precise gagings begun about 25 years ago, to lake elevations observed up to about 40 years previously and assumes a constant regimen of channel, as controlling the discharge prior to the earliest gagings. The outlet channel apparently most subject to change is that at the outlet of Lake Huron, above which sand bars are known to form and shift, and where channels have been deepened for navigation. That the changes here have not seriously affected discharge is indicated by the gagings in 1867–68–69 by D. Farrand Henry, U. S. Assistant Engineer, discussed on page 503, which agreed within one percent of those 30 years later, and by latest gagings of the U. S. Lake Survey.

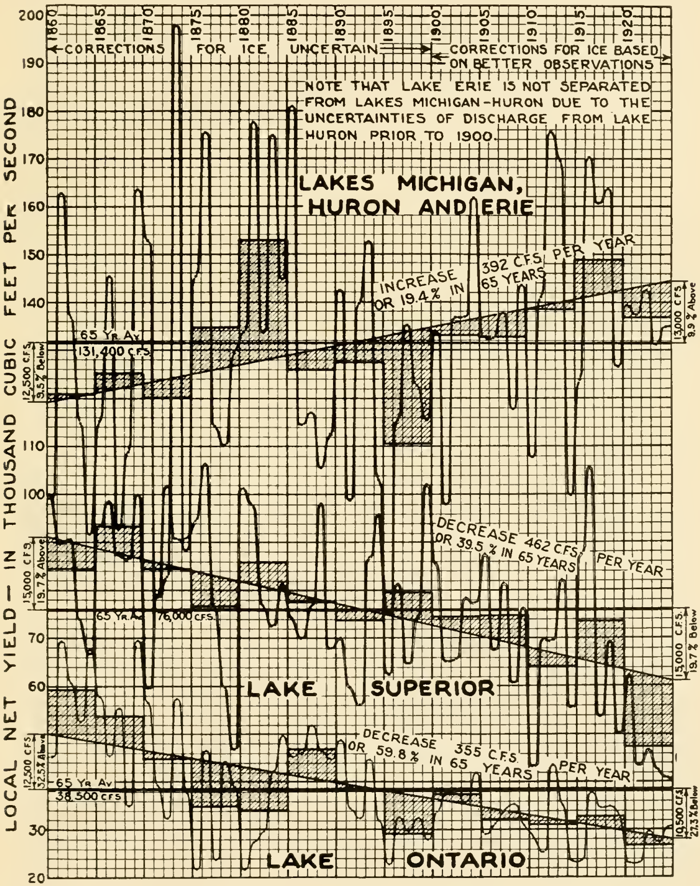
Notes giving the authority for each series of estimates of lake discharge are given on pages 533 and 534.

All discharges presented in the following diagrams are adjusted to give the actual water-yield of the entire drainage area, land and lake, by compensation for diversion, and for rise or fall of surface, also for effect of ice in retarding flow.

It is of interest to note that the two Great Lakes at the opposite ends of this region have shown a steadfast tendency to decrease in water-yield as computed after allowing for changes of elevation, etc. These decreases being respectively at the rate of 40% within a period of 65 years for Lake Superior, and 60% decrease in 65 years for Lake Ontario. These changes are astonishing in amount and are accounted for only partially by the observed general decrease in rainfall over these areas.

In summing up the total for the Great Lakes system as a whole these decreases in water-yield of Superior and Ontario are offset by the increased yield of about 20% found during the 65 year period for Lakes Michigan, Huron and Erie combined. The greater water-yield of these three drainage areas neutralizes the lessened water-yield from the two drainage areas of smaller total yield found around Superior and Ontario.

The smaller yields for Superior and Ontario accord with the smaller rainfalls recorded for those lakes, but in the case of Michigan, Huron and Erie, the increased yield is in opposition to a slightly diminishing rainfall of about 8 per cent.



LONG TERM CHANGES IN SEPARATE LOCAL NET WATER-YIELD OF GREAT LAKES

As shown by discharge, computed from formulas based on daily lake levels, corrected for ice retardation by constant deduction, and adjusted for rise and fall of lakes and for diversions.

WATER-LOSS

The total water-loss, year by year, due to evaporation from lake and land, and transpiration from trees, underbrush and grass, is remarkably uniform and level for Superior; while on Michigan, Huron and Erie a steadfast decline is shown with remarkable uniformity.

The writer is not disposed to attribute this change shown in the **diminished water-loss,** which must be attributed to evaporation and transpiration, from the combined drainage areas of Michigan, Huron and Erie, to the cutting off of the forests and the increased area of cultivated farm land. In general, the popular belief is that this change from forest to farm increases the water-loss.

A steadfast tendency to decrease in rainfall in the Great Lakes region has previously been noted on page 43.

In the following diagrams, the long-term diagram of annual rainfalls shows a decrease for the Lake Superior drainage area from 30 inches to 26 inches rainfall per year, or a total of 13% within 54 years.

A decrease is found for drainage areas of Lakes Michigan and Huron, from 35 inches to 33.2 inches, or a total of 5% within 65 years.

On the Ontario drainage area the rainfall appears to have decreased from 35 inches to 31 inches, or a total of 11% in 65 years.

In general, the diagrams of water-loss or difference between the recorded rainfall, expressed in the weighted average of inches depth over the entire drainage area, and the measured run-off, also expressed in inches over the entire drainage area of land and lake, show a remarkable uniformity, or constant tendency, except in the case of Ontario where a marked change in the rate of water-loss is found at about the year 1890, prior to which time it had been rapidly increasing, but after which date it slightly decreases. No explanation for this is offered. The percent of run-off to rainfall in the early years appears much too large and the water-loss much too small. Errors in the early estimates of discharge of the St. Lawrence River, based on formulas derived many years later, might account for it.

NOTES ON COMPUTATIONS OF ANNUAL WATER-YIELD OF SEPARATE GREAT LAKES

Values of discharge from each of the Great Lakes as used in computing the curves in the preceding diagrams were obtained from the following sources.

Lake Superior, previous to 1887— (St. Marys River)	From Report on Regulation of Lake Erie, 1900, table 119, page 101.
since 1887—	From table received from L. C. Sabin, Assistant Engr. U. S. Engineers Office Sault Ste. Marie, Michigan.
Lake Michigan-Huron, previous to 1900— (St. Clair River)	Values of discharge from various sources were not considered reliable.
since 1900—	From U. S. Lake Survey office, Detroit, Michigan. These values represent the actual discharge, winter and summer, so that no correction for ice retardation was necessary.
Lake Erie, previous to 1899— (Niagara River)	From Report on Regulation of Lake Erie, 1910, table 21, page 103.
since 1899—	From U. S. Lake Survey Office, Detroit, Michigan.
Lake Ontario, previous to 1888— (St. Lawrence River)	From Report on Regulation of Lake Erie, 1910, table 22, page 104.
since 1888—	From U. S. Lake Survey Office, Detroit, Mich., which values represent actual discharges, winter and summer, so that no correction was necessary for ice obstruction.

Deductions for the retarding effect of ice were made according to the schedule given in the table on page 37, except in the case of Lake Ontario since 1888 and Lakes Michigan-Huron since 1900 where the values of discharge as used represented the actual winter flows.

Adjustments were made for the annual fluctuations of the levels of the different lakes by adding to or subtracting from the discharge the quantity of water added to or taken from storage in the respective lakes, as indicated by the change in the mean elevation from January of the year in question to January of the following year.

Additions for diversions were made as follows:

Lake Superior— None.

Lakes Huron-Michigan—Diversions through Chicago Drainage Canal since 1900, in amounts varying from 2990 c.f.s. to 9465 c.f.s. according to date. (See page 172.)

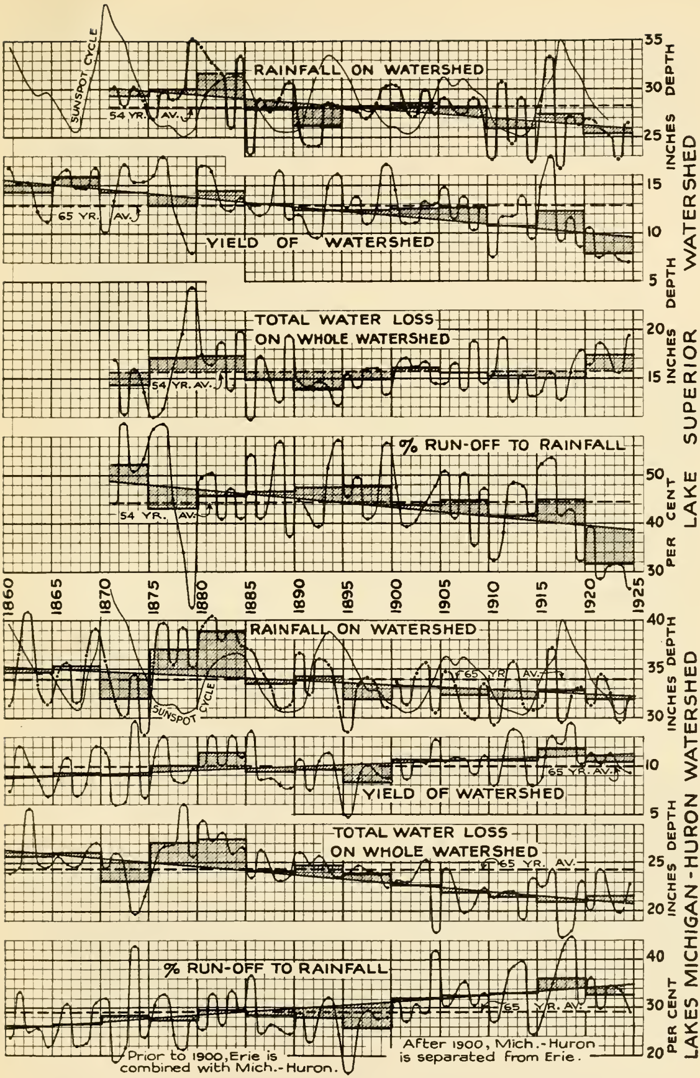
Lake Erie— Diversions through the Chicago Drainage Canal since 1900; also, diversions through the Erie and Black Rock Canals since 1860, varying in amount from 500 c.f.s. to 1000 c.f.s. according to date; and diversions through the Welland Canal since 1882, varying in amount from 1000 c.f.s. to 4500 c.f.s. according to date. (See table of mass curve computations and explanatory notes pages 354 to 365.)

Lake Ontario— Diversions through the Chicago Drainage Canal since 1900.

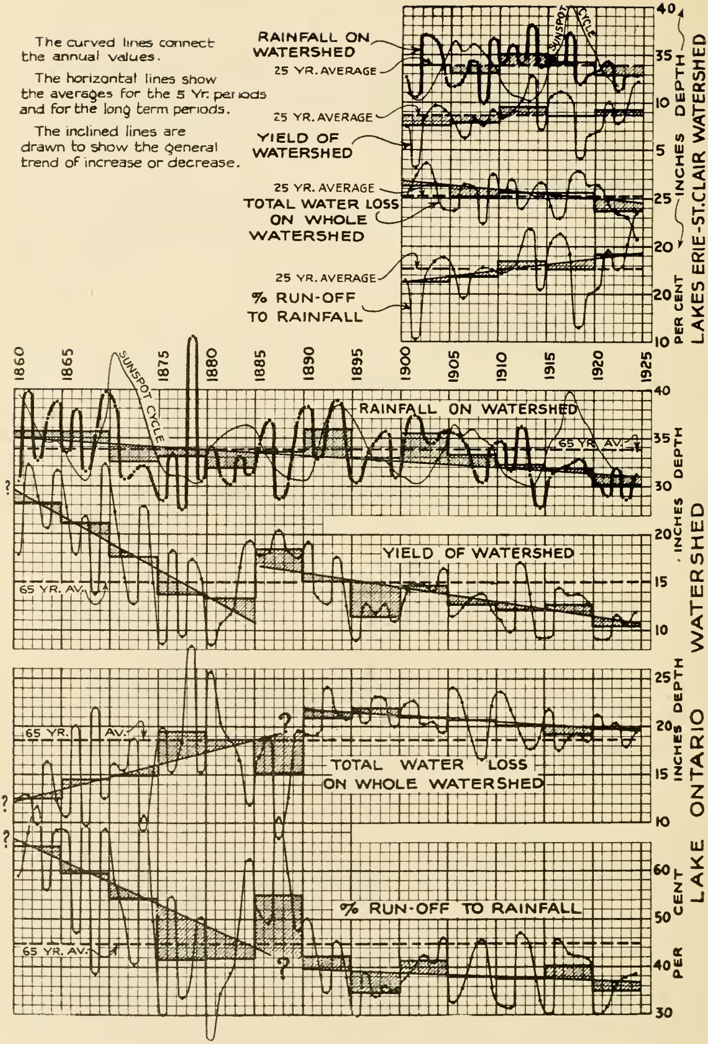
SUN-SPOTS AND RAINFALL

So much is heard now-a-days about the influence of sun-spots on the weather that the sun spot cycle, per the Wolf numbers for each year, (quoted from Mt. Wilson Observatory), has been traced for purposes of comparison on the following diagrams showing the amount of total annual rainfall, year by year, for the drainage area over each lake.

The writer is unable to trace any connection between sun-spot maxima and minima and increase or decrease of rainfall, or water-yield.



LONG TERM TENDENCY TO CHANGE IN ANNUAL RAINFALL AND WATER-LOSS



LONG TERM TENDENCY TO CHANGE IN ANNUAL RAINFALL AND WATER-LOSS

CONSTRUCTIVE CRITICISM INVITED

The foregoing 550 pages were submitted nearly as they now stand, in form of printers proof sheets, to many engineers and scientists having special knowledge of these and similar problems, with an earnest request for all available data, for corrections, and especially for constructive criticism. To some of these, the complete proofs were submitted; to others, only special chapters, as those on Earth-tilt and Evaporation. Particular attention was called to the chapters on Evaporation and Earth-tilt.

The writer has carefully considered all of the replies and has incorporated the suggestions received so far as practicable.

Providence, August 30, 1926.

INDEX

PERSONAL REFERENCE INDEX

DUE DATE

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